MPHIL

An Investigation of the Effect of a Building's Characteristics on the Thermal Environment of Naturally Ventilated Educational Offices

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AN INVESTIGATION OF THE EFFECT OF A BUILDING'S CHARACTERISTICS ON THE THERMAL ENVIRONMENT OF NATURALLY VENTILATED EDUCATIONAL OFFICES

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ABSTRACT

With the climate change, temperatures are expected to increase, making the installation of air-conditioning units in naturally ventilated offices tempting for occupants. The attraction is a quick solution to counteract their thermal discomfort, however, air-conditioning units lead to higher energy demands and increased CO_2 levels. This study investigates the effect of a building's characteristics on achieving thermally comfortable indoor environments in naturally ventilated offices, and in the process highlighting key areas which require further research to find alternative solutions to achieve thermal comfort.

The research focused on educational buildings, with two buildings of different thermal mass located at the University of Bath being used as case studies. The findings suggest that the thermal capacity of a building and the number of occupants per office can play a key role in achieving thermal comfort. Thermal capacity is the most important issue in achieving comfortable indoor temperatures. The second most important factor appears to be the number of occupants in the offices, with the single-occupancy offices being more comfortable for the occupants than multi-occupancy offices. Orientation has the least effect on the thermal sensation of the occupants, with east-facing offices being more prone to overheating than offices of other orientations and thus should be avoided. These findings highlight key areas to be addressed when constructing or refurbishing naturally ventilated educational offices in the UK in order to avoid the installation of air-conditioning units.

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ABBREVIATIONS

AC	Air conditioned
ACE	Department of Architecture and Civil Engineering (6E)
CO_2	Carbon dioxide
CV	Comfort vote
DEC	Display energy certificate
HVAC	Heating, ventilating and air conditioning
IAQ	Indoor air quality
NOAA	National oceanic and atmospheric administration
NV	Naturally ventilated
ME	Department of Mechanical Engineering (4E)
PASCOOL	Passive cooling
PROBE	Post-occupancy review of buildings and their engineering
RH	Relative humidity
SBS	Sick building syndrome
SCAT	Smart controls and thermal comfort
TRV	Thermostatic radiator valve

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LIST OF SYMBOLS

A	Area (m^2)
ATS	Adjusted thermal sensation vote
C	Specific heat capacity ($Jkg^{-1}K^{-1}$)
C_m	Heat capacity (areal) ($kJm^{-2}K^{-1}$)
C_v	Ventilation conductance (WK^{-1})
clo	Unit of clothing insulation
CV	Thermal comfort vote
f_r	Response factor
d	Thickness of material (m)
M	Thermal comfort vote
ppm	Parts per million
R	Thermal resistance
t	Period of variation (s)
T	Air temperature (°C)
T_{in}	Indoor air temperature (°C)
$T_{in\ (9am\text{-}6pm)}$	Indoor air temperature between 9am and 6pm (°C)
T_{out}	Outdoor air temperature (°C)
$T_{time\ max}$	Corresponding outdoor temperature at time of maximum indoor temperature (°C)
$T_{time\ min}$	Corresponding outdoor temperature at time of minimum indoor temperature (°C)
U	Thermal transmittance ($Wm^{-2}K^{-1}$)
Y	Thermal admittance ($Wm^{-2}K^{-1}$)
δ	Penetration depth (m)
λ	Thermal conductivity ($Wm^{-1}K^{-1}$)
ρ	Density (kgm^{-3})

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Chapter 1

INTRODUCTION

Naturally ventilated buildings are usually perceived by occupants as healthier and more comfortable than air-conditioned buildings and they consume less energy. With the climate change more building owners will be tempted to install air-conditioning units in their buildings in an attempt to maintain comfortable indoor temperatures. This study investigates how a naturally ventilated building's properties (thermal capacity) and characteristics (office orientation and occupancy levels) affect the indoor air temperatures reached in its offices. The findings are then used to make suggestions on how a building's properties and characteristics can be used to achieve thermally comfortable naturally ventilated spaces. The recommendations apply to new constructions and refurbishments of educational office buildings, which form the sample of buildings used in this study.

This chapter outlines the motivations for the present study and its importance in the wider context. The chapter is divided into three main sections:

1. Motivation
2. Research questions and objectives
3. Work scope and thesis structure

1.1 MOTIVATION

This section summarizes some of the issues that influenced and helped develop this research. A variety of areas were investigated, including reasoning for the type of buildings that are studied.

1.1.1 Climate Change

Rising global temperatures are one of the primary factors making climate change an indisputable reality (IPCC, 2007). Eleven out of the twelve warmest years since 1850 were recorded between 1995 and 2006 (IPCC, 2007), and if there is no change in our current activities global temperatures are expected to rise by 3°C within this century (UNFCCC, 2007). Comparisons of temperature changes for the UK up to 2004 with respect to the baseline (1961-1990 average temperature) used by the UKCIP02 (UKCIP, 2002), have been developed by the Met Office (Perry, 2006) and indicate the rising temperature between each season (Figure 1.1).

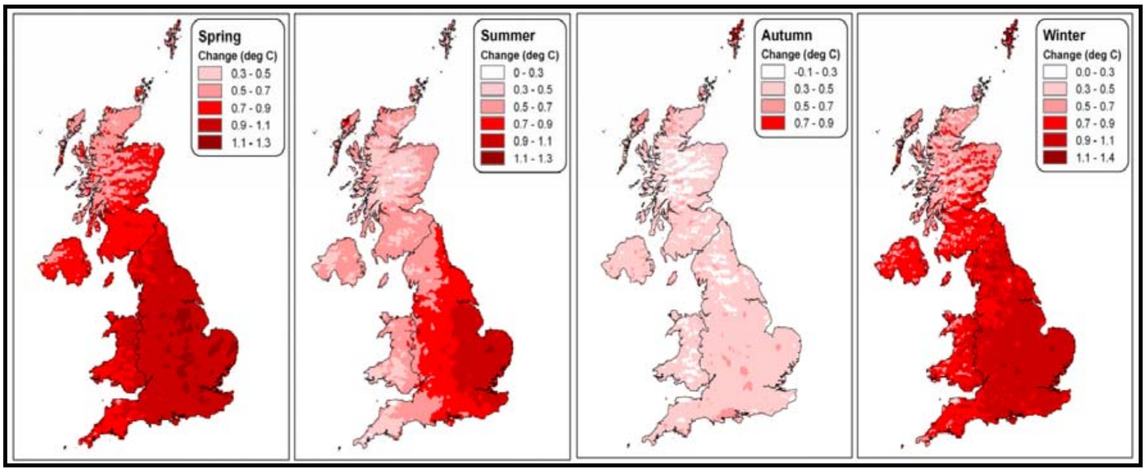

Figure 1.1: Seasonal average temperature change (°C) from the 1961 - 1990 average to the 1991-2004 average.

Reference: Perry, M. 2006. Climate Change Memorandum No21 : A spatial analysis of trends in the UK climate since 1914 using gridded datasets. Met Office.

The pace and effects of climate change have been underrated (Greenpeace Australia Pacific, 2009) and its atrocious consequences are already upon us, years earlier than expected (Shallhorn, 2009). The 2003 European heat-wave that caused the loss of lives of more than 52,000 people (Larsen, 2006) came twenty to thirty years earlier than anticipated (THE, 2003). Despite Britain being one of the least affected countries during that summer, some offices were severely affected causing financial losses (Roaf *et al.*, 2005).

Energy consumption is one of the key issues increasing the emission of anthropogenic greenhouse gases (GHG) (IPCC, 2007) causing climate change, and hence it should decrease unless it is from a sustainable source. It is predicted that there will be more frequent heat-waves in the UK as a result of climate change, causing a rise in demand for the installation of air-conditioning (AC) systems (Met Office, 2009a). Considering the fact that the world's building sector already consumes approximately half the energy produced worldwide, (Roaf *et al.*, 2005) people should learn to adapt to these changes when inside buildings, by using assisted ventilation or changing their clothing rather than installing ACs, which increase energy demand, leading to the vicious cycle of increasing CO_2 emissions etc.

To emphasise the effect AC systems have on the GHG emissions, consider the US, which consumes almost a quarter of the world's energy (Roaf *et al.*, 2005). A fifth of that energy is used for AC units, thus causing the US to emit around 5% of the worldwide greenhouse emissions from its AC systems alone (Roaf *et al.*, 2005). In the UK approximately 55% of the energy consumed in offices is for heating, ventilating and air-conditioning them (Perez-

Lombard *et al.*, 2008). Climate change thus puts more strain on us to ensure that the occupants of the buildings are in a comfortable indoor environment, whilst avoiding the installation of AC systems.

1.1.2 Naturally Ventilated or Air-Conditioned Buildings

Although ACs provide optimal indoor temperatures, occupants are no longer just "*passive receivers"* like they were during the industrial revolution where they accepted the mechanically-influenced environments given to them (Forwood, 1995). Instead, they demand more control over their thermal environment and want a rapid response to any discomfort they experience, which is harder to achieve in AC buildings (Bordass *et al.*, 1993). Naturally ventilated (NV) buildings on average offer more adaptive opportunities for the occupants, such as openable windows, than AC buildings (Nicol *et al.*, 1999).

NV cellular buildings consume approximately 2.8 times less energy when compared to an identical AC building, in order to deliver, on average, the same services (Scrase, 2000), hence NV buildings should be more favourable for both building owners (low running costs) and tackling climate change (less CO_2 emissions). With the increase in temperatures (due to the climate change), the installation of ACs in current NV buildings is likely to increase and consequently, so should research on refurbishments of NV buildings.

Further, the expectations of the occupants in NV buildings are more relaxed when compared to the expectations of the occupants of identical AC buildings (Brager and de Dear, 1998, Fountain *et al.*, 1996). NV building occupants are more tolerant of the temperature changes throughout the day and over the different seasons, in contrast to the AC building occupants who are not happy with temperature variations throughout the day and for temperatures away from their expected ones (Brager and de Dear, 1998).

On the other hand, studies have shown that there are more complaints in buildings with AC units compared to NV ones (Baker and Steemers, 2000), indicating that higher energy consumption does not necessarily make the indoor environment more comfortable for the occupants. The usage of air-conditioning systems increases the frequency of sick building syndrome (SBS) symptoms, and in fact, it is much higher than a similar NV building, even as much as 200% higher (Seppänen and Fisk, 2002). As health and motivation for the performance of tasks of occupants within a building are both affected by the indoor environmental conditions (Fisk *et al.*, 2009, Seppänen and Fisk, 2002, 2004, 2006), such as indoor temperature (Seppänen *et al.*, 2006) and indoor air quality (Wyon and Wargocki, 2006a), emphasis should be placed on NV buildings and how to improve them.

Further, installing ACs does not only make the occupants dissatisfied within their working space, but also makes the building more expensive to operate, as energy bills can be up to five times higher than for the corresponding NV building. More importantly, ACs have a negative impact on the climate making it even harder to avoid its impacts (Roaf, 2007). Humphreys *et al*. (1995) suggest that NV buildings are a viable option in the UK. Over winter they suggested that buildings are likely to require heating but if the offices have been designed carefully they will require infrequent cooling in the summer.

Case studies suggest that NV buildings are feasible and in some cases natural ventilation solutions can be used to replace AC systems, which are over-used nowadays (McCartney and Nicol, 2002, Pasquay, 2004). Designers and engineers should be conservative regarding the necessity of installation of AC systems in buildings in the future. Even if NV buildings cannot provide comfortable conditions to the occupants, the next step should be to investigate the applicability of hybrid systems, where parts of the building are NV and other parts of it are AC. Hybrid systems consume approximately the same energy as NV buildings on a monthly basis (Karyono, 2000) and the adaptive opportunities can still apply to them (Tuohy *et al.*, 2007). As Forwood (1995) suggested the main aim should be to provide comfort for people and not just to heat or cool buildings.

1.1.3 Building Characteristics and their Effect on Thermal Comfort

Humphreys (1994) noted that people were sensitive to sudden excessive temperature swings, and hence in order to avoid discomfort, careful designing of the buildings is necessary. The effect the outdoor climate has on the indoor climate of a building depends on its characteristics, such as the transmission of heat through the fabric of the building, which depends on the insulation of the building and its thermal mass or the number of windows etc. (Raja *et al.*, 2001).

Thermal mass, defined as the ability of a material to absorb, store and release heat at a later time, plays an important role in the internal temperature of spaces (SEA, 2008). Discomfort is more likely to arise in a lightweight building (low thermal mass), as it responds very quickly to solar gains unlike a heavyweight building, taking the indoor temperature beyond the comfort limits (Figure 1.2) (Baker and Steemers, 2000, Roaf, 2007). The higher the thermal mass, the more heat energy can be stored (Horton, 2006). As can be observed from Figure 1.2, direct sunlight on a lightweight building causes an immediate overheating, whereas for heavyweight buildings, the solar gains are absorbed by the structure, and heat is released later in the day when the external temperature starts decreasing. The amount of thermal mass a building has depends on its construction.

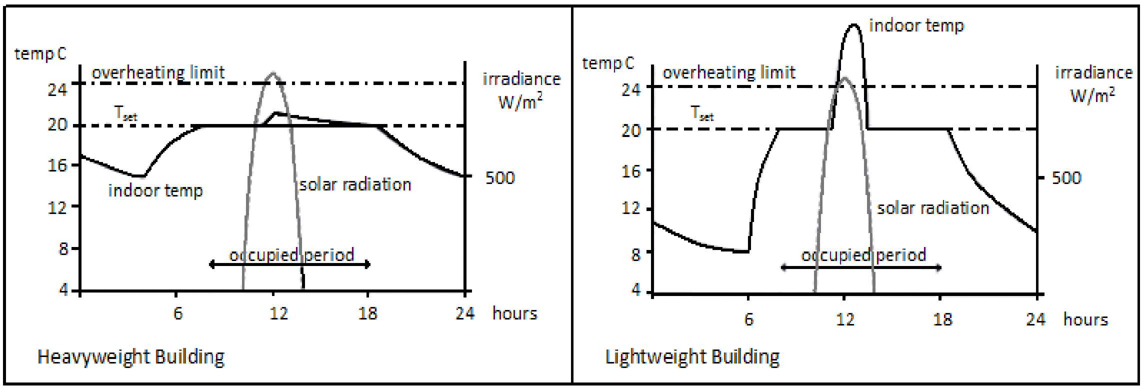

Figure 1.2: The effect of solar gains on the indoor temperature of heavyweight and lightweight buildings.

Reference: Modified from Baker et al. (2000) pg.39.

Raja *et al*. (2001) and Tuohy *et al*. (2007) have shown that heavyweight buildings are overall cooler than the lightweight ones, and as suggested by Roaf (2007), if buildings have more thermal mass, it can assist in maintaining a comfortable indoor temperature during heat-waves or even cold snaps. A lightweight building has a high risk of overheating whether shaded or unshaded, in comparison to a heavyweight building (Tuohy *et al.*, 2007). The higher the thermal mass of the building, the lower the annual heating demand, and the more comfortable the occupants are (Tuohy *et al.*, 2007).

There is extensive research on the effect of thermal mass on indoor air temperatures (Balaras, 1996) and abundant information on what affects thermal comfort of occupants in internal spaces, such as controls, clothing etc. and their effect on productivity and health (Parsons, 2003). Nevertheless, there is minimal information on the extent of the effect of thermal mass and thus the temperature swings on the occupants thermal comfort in NV buildings. Although Raja *et al*. (2001) have shown the effect of thermal mass on the indoor air temperature of the free-running buildings, they have not correlated the comfort votes of the occupants with the type of buildings. Tuohy *et al.* (2007) have investigated the correlation of thermal mass on the temperatures and when they are likely to cause discomfort, but not by how much.

Another factor that affects indoor air temperature is the orientation of the building, as the internal gains will vary. A study on houses in Dhaka, Bangladesh, which has a tropical climate, found that buildings with thicker walls are significantly more comfortable, especially over summer (Mallick, 1996). It was also observed that north-facing houses are much cooler, followed by east-facing, then west-facing, and lastly south-facing ones. However, it was mentioned that north-facing rooms were the least preferred option as they receive no direct sunlight. A study in Indonesia showed that a north-south orientated building, which had a lot of protection from direct sunlight, had a significantly lower temperature ($T_{average}$ = 24.4°C) than another building which was east-west orientated ($T_{average}$ = 27.8°C) (Karyono, 2000). In France, the highest temperatures were recorded in east- and west-facing offices (Moujalled *et al.*, 2008). There is no detailed research on the relationship between orientation, indoor air temperatures and thermal comfort of the occupants in NV buildings, and hence this appears to be a key area which requires further development.

1.1.4 Educational Buildings

Universities during this epoch are regarded as “small cities”, due to their high population, size and the wide range of activities that take place (Alshuwaikhat and Abubakar, 2008), and hence unsurprisingly, educational buildings are responsible for high energy consumption within a country’s non-industrial energy usage (IEA, 2004). The higher education (HE) sector occupies 27% of the total office stock in the UK (THE, 2005). Offices in UK are the second largest energy consumers (17%) of the non-domestic sector after the retail (22%) (Perez-Lombard *et al.*, 2008). In the UK the non-domestic building sector is responsible for 20% of its carbon dioxide emissions (Barlow and Fiala, 2007) and hence targeting that part of the non-domestic sector it is recommended (Perez-Lombard *et al.*, 2008).

The UK HE sector alone consumes 5.2billion kWh of energy per annum (TSO, 2006). In order to appreciate the amount of energy consumed by HE in the UK, it is compared with the average number of households that would consume the same amount of energy per year, which is approximately 220,000[i], or three times the energy consumed by all households in Bath and

[i] Energy consumed by an average household per year in the UK is 23,500 kWh Chan, J. & Williams, L. (2009) Maps showing total domestic, industrial and commercial energy consumption at local authority level. *Department of Energy and Climate Change,* http://www.berr.gov.uk/files/file41497.pdf. March 2009.

North East Somerset[ii]. Consequently, the HE sector can play a leading role in the reduction of greenhouse gases.

Replacing the heat lost through the building fabric such as through walls, floors and ceilings and due to the ventilation, accounts for 67% of the energy consumption of NV university buildings (Carbon Trust, 2007). Therefore, the building fabric has to be improved in order to minimize the losses and hence reduce bills as well as improve the comfort of the occupants.

1.2 Aim, Research Questions and Objectives

The aim of the study is to investigate how an educational building's properties and characteristics, such as its thermal capacity and its office arrangement, affect the temperatures reached indoors, and to what extent that impacts the thermal comfort of the occupants.

In order to examine the above aim, the following research questions shall be answered:

1. How does the indoor air temperature and the thermal comfort vote compare for two buildings of different thermal mass?
2. Does the orientation of the offices (north, south, east or west) have a significant impact on the thermal comfort of occupants?
3. How does season affect the thermal comfort of occupants?
4. How does the office size affect the indoor air temperatures reached in the offices and the thermal comfort of the occupants?
5. What adaptive opportunities do the occupants use, and how does this influence their comfort vote?

The purpose of this study is to research into the effect of the building's properties and characteristics on the indoor air temperatures of its offices. The findings will be used to make suggestions on refurbishments of naturally ventilated educational office buildings.

This investigation will benefit people who are involved in constructing and refurbishing educational buildings whilst contributing to existing knowledge in improving the thermal indoor environment of offices. As a consequence of this research, the University of Bath will benefit by finding out more on the current performance of its buildings and the occupants' perception of the indoor air temperatures.

1.3 Work Scope

The study commenced as a summer research project (August 2008), funded by EPSRC and the Department of Architecture and Civil Engineering (ACE) of the University of Bath. The thermal performance of the offices of the Department of ACE and the Department of Mechanical Engineering (ME), which are located in two buildings with different levels of thermal mass, were investigated. The summer findings suggested a significant difference in the air temperatures in the two buildings with some offices suffering from over-heating. It was

[ii] Bath and North East Somerset has approximately 72,521 households BNESC (2008) Impact of energy saving actions across the district. In: *Bath & North East Somerset Council (BNESC).*

consequently decided to extend the study over a year to investigate their thermal performance over the different seasons. The occupants' perceptions and behaviours with respect to their thermal environment were also incorporated.

Both single- and multi- occupancy offices were studied in both buildings. The reason for studying offices of different occupancy is that almost 50% of the office occupants prefer having their own offices, but currently only 28% have a cellular office, in contrast to the 62% which share open-plan offices (Wheeler and Almeida, 2006). Since occupants prefer cellular offices, it is important not only to study multi-occupancy ones which is the norm, but to also compare the performance of offices of different occupancy and how they are perceived by the various occupants.

SUMMARY

The climate change has put pressure on us to create and maintain NV buildings, to reduce unnecessary energy consumption. Since educational buildings are responsible for a large amount of the UK's non-industrial energy consumption, it is important not to overlook their energy performance. In this study the effect of the buildings' properties and characteristics on the indoor air temperatures is investigated. The findings will be used to make suggestions on refurbishments of naturally ventilated educational office buildings, whilst directly benefiting the University of Bath. The following chapter places the study that has been performed in context with other research performed to date.

Chapter 2

LITERATURE REVIEW

A large proportion of humans spend most of their lifetime (about 90%) indoors (Clements-Croome, 2006, Lush, 1992), and therefore it is important to achieve pleasing indoor environments. It has been constantly pointed out that low energy buildings should be designed that do not sacrifice thermal comfort (Baker and Steemers, 2000). The energy crisis in the 1970s was the main alert for building environmental engineers to start looking at making more energy efficient buildings (de Dear and Brager, 2001), with one of the measures at the time being to lower indoor temperatures in offices by 2°C during the heating period (Vischer, 1989). Prior to then, buildings were mostly isolated from the external conditions (de Dear and Brager, 2001). Although over winter buildings in UK require heating, Humphreys and Nicol (1995) suggested that NV buildings are a viable option, and if designed carefully the usage of ACs should be infrequent.

Current literature on the various indoor environment factors and some of their implications are considered in this chapter. Reference is made to existing case studies for offices (both educational and commercial). The chapter is divided into two main sections:

1. Thermal comfort
2. Naturally ventilated buildings

2.1 Thermal Comfort

Thermal comfort is defined as ''that condition of mind which expresses satisfaction with the thermal environment'' (BS EN ISO 7730, 2005). The six basic factors that affect the thermal comfort of occupants are (Fanger, 1970):

1. air temperature,
2. air velocity,
3. radiant temperature,
4. humidity,
5. clothing,
6. metabolism.

Research on the effects of the indoor environment on humans dates back to 1919, when there was an increase in AC installations and hence an interest developed in relating the effect of temperature and humidity on humans (McIntyre, 1980). However, psychological research on the effect of indoor climate on people's sensations did not commence until 1945 (McIntyre, 1980).

Thermal comfort models have been developed in order to predict thermal comfort of occupants in buildings (Nicol, 2008). There are two main types of thermal comfort models; the static model and the dynamic model (Brager and de Dear, 1998). The static models, such as Fanger's model, are based on climate chamber studies / controlled environments and consider the occupants as passive receivers of their surrounding environment. Dynamic models, however, are based on field study findings and expect the occupants to interact with the environment in order to achieve thermal comfort (Brager and de Dear, 1998, Nicol, 2008).

2.1.1 Field Studies and Climate Chambers

Data regarding the indoor climate can be obtained in one of two ways (Humphreys, 1992):

1. Climate chambers: have a controlled environment (Nicol, 2008).
2. Field studies: do not have the controlled environment of climate chambers, and they are usually carried out to obtain answers to specific enquiries concerning a particular building (McIntyre, 1980). It has been repeatedly shown that in real life people are comfortable over a wider range of temperatures rather than in chambers (Humphreys, 1976, 1996, McIntyre, 1980).

Both ways are deemed essential as they both have their advantages and disadvantages (McIntyre, 1980), and as Parson (2002) suggested the roles of these two types of research should be seen as complementary to each other. However, carrying out real world research offers the advantage of looking at a particular scenario (environment of an office or school etc.), and evaluates how to improve the design aspects of the space, rather than an assumed situation (Robson, 2002).

Nicol (2008) has categorized field surveys into three levels. For a level 1 study, air temperature is measured and no subjective data are collected. When subjective data are collected and the thermal environment of the space is measured such as water vapour, air temperature etc. the study falls under level 2. A level 3 study is much more detailed with subjective responses and all environmental factors are measured so that one can calculate the heat exchanges taking place between the occupant and their surrounding space.

This field survey is categorized as a level 2 study as air temperature is monitored and subjective data collected (further information can be found in the Chapter 4). As Nicol (2008) mentions it does not matter which type of survey one decides to carry out, provided that the environment the occupants are subjected to is representative of their daily environment. Further, the subjects should be allowed to change their environment as they would normally do (by opening windows, for example).

2.1.2 Comfortable Buildings

Buildings are considered comfortable when their indoor environmental conditions are '*predictable*' on a daily basis, as temperatures tend to lie within the comfort range and occupants know what to wear (Leaman and Bordass, 2001). Occupants want buildings that respond quickly to them, and where they have the options to resolve any of the unexpected conditions that may occur (Leaman and Bordass, 1999a).

Even the most comfortable buildings still have 5-10% of occupants dissatisfied or uncomfortable with their indoor environment (Leaman and Bordass, 2007). Having thermally comfortable internal spaces reduces complaints and can perhaps increase the productivity of the occupants. Fanger (1970) explains that people's performance (physical and intellectual) is highest when they are in thermal comfort. However, in contrast, Parsons (2003) argues that a comfortable environment reduces complaints but may decrease performance, especially if a boring task is being performed. Similarly, Wyon and Wargocki (2006b) found that large temperature swings throughout the day, although caused discomfort, in fact increased the rates of work due to stimulation of the workforce.

Leaman and Bordass (2001) concluded that buildings which are perceived by occupants as performing better over summer than winter, are thermally more comfortable than those overheating in summer and sometimes overheating in winter. They also suggested that over summer the most comfortable buildings may be on the cool side of the thermal comfort scale.

Humans differ not only biologically but also in their dressing habits, and consequently, it is expected that there will be discrepancies in what is deemed as a comfortable temperature by occupants of the same space (Wyon and Wargocki, 2006b). Fanger (1970) argues that it is not feasible to have everyone present in a room content at any given time with their thermal environment, but instead designers must aim to satisfy as many as possible, whilst ASHRAE (2005) suggests that an 80% satisfaction for occupants with limited activity within an indoor thermal environment is reasonable.

People tend to feel more often uncomfortably cold or hot in their offices rather than in their homes (Karjalainen, 2009). Constant temperatures in offices are almost always perceived as comfortable, as unpredictable temperature changes tend to cause discomfort (Vischer, 1989). Humphreys (1992) suggested that diurnal indoor air temperatures should not have a variation of more than ±1°C to maximize comfort of the occupants, and although ±2°C might still be satisfactory, it is more noticeable and hence more likely to cause discomfort. Contrarily a study performed in offices in north-west Pakistan proposed that people are likely to be comfortable with up to 11°C difference between summer and winter, with minimal clothing adjustments and unconscious changes by the occupants such as changes in posture or skin temperature tolerance (Humphreys, 1994).

Occupants are likely to use adaptive opportunities, such as changing clothing, posture, activity or opening a window, closing a curtain etc., in order to maintain their comfort if there are changes to their indoor environment, and counteract any discomfort (Nicol and Humphreys, 1973, Raja *et al.*, 2001). Discomfort may occur when the expectations for a certain environment are not the same as the actual (Humphreys, 1992). For example, one day it is unexpectedly colder than the other days and consequently people are not dressed for that weather and cannot change it (Humphreys, 1992), unlike in seasonal changes where people learn to adjust their clothing (McIntyre, 1980).

Thermal comfort is regarded as a chronic problem and still holds one of the top ranks on complaint lists of offices according to the PROBE* occupant survey studies (Leaman and Bordass, 2001). It has been suggested that this could be related to the buildings becoming more dependent on computer-controlled systems, and hence the occupants perceiving that they have less control of their environment (Leaman and Bordass, 2001). Humphreys (1996) suggested that comfort is more likely to be achieved if each occupant has control over their thermal environment rather than their environment being controlled by others who may not even be present in the office.

In general, indoor thermally comfortable temperatures for occupants vary depending on the country with one of the highest recorded in Iraq (32°C) and one of the lowest in the UK (17°C) (Humphreys, 1976). This difference cannot be explained solely in terms of dressing habits, but also by other contributing factors (Humphreys, 1996).

People do not always like to feel neutral (Humphreys and Hancock, 2007). In some circumstances, they like to feel slightly warmer, and in the UK people nearly never want to feel cool or cold. In a study performed by Humphreys and Hancock (2007) in university lecture rooms and dwellings in the UK, indicated that people do not have one desired vote only. Although neutral was the most popular desired comfort vote, they tend to change depending on the occasions, but it was highly unlikely for one to move away from their typical desired value by more than two scale units (Humphreys and Hancock, 2007).

2.1.3 Indoor Temperature Standards

The Workplace (Health, Safety and Welfare) Regulations 1992 suggest that temperatures in offices have to be reasonable but no reference is made to specific temperatures (Workplace Regulations, 1992), hence the word reasonable is left open to interpretation. Other sources suggest various temperature ranges for indoor temperatures in the offices of the UK, and reference is made to the various other suggestions:

1. Acceptable UK indoor temperatures lie between 13°C and 30°C, depending on what type of work the workers are performing, with the sedentary being nearer to higher end of the spectrum, and the Approved Code of Practice of the Workplace Regulations 1992, suggests 16°C as the minimum temperature offices for places where work is sedentary (HSE, 2007).
2. Summer room temperatures, T_{indoor} , for NV buildings depend on the mean outdoor temperatures, T_{outdoor} , where $T_{\text{indoor}} = 0.33\ T_{\text{mean oudoor}} + 18.8 + 3$ (BS EN 15251, 2007). It is

* PROBE study – defined as the Post-occupancy Review OF Buildings and their Engineering, was a project that lasted seven years, studying how buildings were performing after they were occupied, in order to improve the designs of buildings. Cohen, R., Standeven, M., Bordass, B. & Leaman, A. (1999) Probe Strategic Review 1999. DETR.

suggested that for indoor temperatures higher than 25°C assisted ventilation such as fans could be used to compensate for the high temperatures (BS EN 15251, 2007). Increasing the air-speed by using fans for example, will increase the evaporation of sweat, and hence will give a sensation of coolness, but there is a limit to the extent that increases in air-speed will compensate for the high temperatures (Monash University, 1999). During the winter period, buildings with heating should have indoor temperature between 20°C and 24°C (BS EN 15251, 2007).

3. Temperatures for university offices should be between 19-24°C (Carbon Trust, 2007).
4. The indoor comfort temperature for the buildings lies within the range of 22-24°C for summer for AC buildings and between 21-23°C over winter (Steemers, 2006). For the NV buildings, CIBSE (2006) only suggests that it is acceptable for the indoor temperature where work is sedentary such as in offices to exceed 25°C by up to 5% of the total time occupied.
5. The British Council of Offices suggested that indoor air temperatures for offices in NV buildings are between 23°C and 25°C over summer and 18°C over winter (Ward, 2004).

It can thus be concluded that there is ambiguity in the temperature ranges for offices in the UK and there are no strict temperature limits, unlike other countries. Spain for example, has passed a regulation to reduce its energy consumption, where minimum summer temperatures should be 26°C and maximum winter temperatures should be 21°C for AC buildings (non-residential and public with some exemptions) (IEA, 2008). Portugal, on the other hand, has specific indoor air temperatures of 25°C for summer and 20°C for winter (Guedes *et al.*, 2009).

Regarding the higher education sector, the Carbon Trust's suggestion of 19-24°C would be the most applicable. However, in the same report it is argued that for every 1°C of overheating there is an approximate 10% increase in fuel consumption, thus a more narrow range has to be made in order to limit unnecessary energy usage. Some organizations in the UK set their own temperature limits. For example, City University, UK, has developed a policy for maintaining an indoor temperature for its offices of 19°C to 21°C for the heating period and 23±3°C for the cooling period for formal offices and 25±3°C for informal offices (McKinnell, 2006).

Guedes *et al*. (2009) revealed that in Portugal about 80% of office spaces were heated in winter independently of their indoor air temperature (85% heated when $T_{in} \geq 25°C$), whereas 15% of the office buildings were cooled in winter even when the indoor temperature was lower than 20°C. Karjalainen (2007) concluded a similar finding in his study in Finland. Occupants open their windows often during the heating period to cool the indoor environment. Similar cases are likely to exist in the UK too, at least where there is lack of control of the occupants over their environment. As Vischer (1989) mentioned, it is more energy consuming to cool down a room than to warm it up, as heat is also generated by computers, occupants and lights. Cooling buildings in winter when they are supposed to be cool by themselves is unnecessary energy consumption, likewise to heating them without limits.

A field study performed by the US Environmental Protection Agency indicated that as temperatures moved closer to the lower spectrum of the recommended indoor air temperatures for winter (lower than 23°C), the number of occupants experiencing SBS symptoms decreased (Mendell and Mirer, 2009). Over summer, higher air temperatures (higher than 23°C) decreased SBS symptoms. On the contrary, based on findings from a study in AC offices, Fang *et al*. (2004) suggested that SBS symptoms decrease as air temperature decreases, emphasizing the importance of having the correct indoor air temperature in offices. There is no indication that the Carbon Trust's (2007) suggestion for offices in winter to be 19-24°C has been tested with the occupants and how they perceive them.

There is a strong linear relationship between the indoor air temperature and outdoor temperatures for naturally ventilated buildings, unlike for the conditioned buildings (heated or cooled) were the relationship follows a curve (Humphreys, 1981). Humphreys and Nicol (1995) suggested the following target indoor temperatures (T_{in}) based on the outdoor temperatures (T_{out}):

$$\text{If } T_{out} < 12°\text{C} \quad \text{then} \quad T_{in} = 19°\text{C}$$

$$\text{If } T_{out} \geq 12°\text{C} \quad \text{then} \quad T_{in} = 0.534T_{out} + 12.9°\text{C}$$

Various methods have been suggested to find the optimal indoor temperatures to minimize the percentage of people dissatisfied under certain environmental conditions. McIntyre (1980), for example, suggested that the subjective temperature, T_{sub} (°C), i.e. the temperature that would provide comfort for the occupants, can be calculated using the following equation:

$$T_{\mathrm{sub}} = 33.5 - 3I_{\mathrm{clo}} - (0.08 + 0.05I_{\mathrm{clo}})\mathbf{M}$$

where I_{clo} (clo units) is the clothing insulation and **M** is the metabolic rate (W/m^2), and the metabolic rate for a person doing normal office work is 75 W/m^2 (McIntyre, 1980).

A study performed in Japan and Korea revealed that temperatures office occupants were exposed to up to an hour and a half before their current environment influences their thermal comfort vote for the current temperatures (Chun *et al.*, 2008). People who were exposed to warmer temperatures prior to the experiment were perceiving the indoor environment to be cooler than those who were exposed to cooler temperatures prior to the test. Leaman and Bordass (1999a) suggested that perceived cooler buildings are regarded as healthier than warmer ones in the UK.

2.1.4 Gender and Comfort

Laboratory investigations at the Human Thermal Environment's Laboratory at Loughborough University simulated office environments for 32 subjects to find the effects of gender on thermal comfort (Parsons, 2002). The conclusions were that whether male or female, there was no effect on thermal comfort for warm and neutral conditions, unlike in cold conditions, where women felt more cold than men. In another study, it was suggested that differences do occur in thermal comfort between males and females and it can be explained due to the differences in the clothing insulation they wear (Parsons, 2002). However, another study in NV buildings revealed that there are no significant differences in the clothing insulation chosen by office occupants amongst genders (De Carli *et al.*, 2007), but, overall, females make more changes than males to achieve the same comfort (Parsons, 2002). Humphreys (1976), on the other hand, in a comparison of existing field studies up to the 1970s, concluded that women tend to prefer temperatures 0.5°C cooler than men which is not regarded as a significant difference.

Some studies show that there is no significant difference between men and women and their comfort vote, although females tend to express thermal dissatisfaction more often when compared to males (Cena and de Dear, 2001, Fanger, 1970, Parsons, 2003). Other studies have shown that both genders have the same comfort vote for neutral and warm conditions provided they wear the same clothing and they are performing the same activity, but females tend to feel colder in cooler conditions (Parsons, 2002). Other studies, however, have shown the opposite; there were significant differences between the two genders and it was more obvious in the office environments (Karjalainen, 2007). This indicates the importance of having a fair sample comprising both genders in the study. Each study is different with respect to how male and female subjects perceive their indoor environment, and assumptions cannot be made as to how the opposite sex will perceive the environment should one sex be used in the study.

Karjalainen (2007) noted that females feel uncomfortable more often with the temperature whether it is warm or cold and they are also more often dissatisfied with the room temperatures than males, and they perceive that they have less control of the same environment than men. It was also suggested that women are more sensitive to the temperatures they are exposed to and more judgmental than men, and if females are satisfied it is highly unlikely that males will complain. These findings cannot be explained by activity, as all subjects were working in the same offices, or by clothing, as although women were dressed lighter than men the differences were insignificant. Griefahn *et. al* (2001) looked into the effect of draught and temperature on comfort, and concluded that women felt uncomfortable more often and more on the slightly cool side due to the draughts, compared to men.

2.1.5 Room Temperature, Productivity and Performance

Parsons (2003) defines performance as *"the extent to which activities have been carried out to achieve a goal"*, and productivity as *"the extent to which activities have provided performance in terms of systems goals"*. Good indoor air quality and thermal comfort are essential for office workers to be satisfied, comfortable and achieve high performance (Charles *et al.*, 2005). It has been suggested that the relationship between comfort and productivity is linear and positive (Leaman and Bordass, 2006).

Studies regarding temperature, productivity and performance are contradictory amongst themselves. Some suggest that a temperature outside the group's thermal comfort zone decreases productivity (with contradicting percentage levels) (Fanger, 1970, Griffiths and McIntyre, 1975, Niemela *et al.*, 2002), whereas other studies suggest that if temperatures are not in the comfort range they stimulate people and increase their performance (Parsons, 2003, Pepler and Warner, 1968, Wyon *et al.*, 1979, Wyon and Wargocki, 2006b). It can thus be concluded that the relationship between comfort and productivity depends on the occupants of each building, emphasizing the importance of post occupancy evaluations.

In a study on the relation of fatigue and productivity on temperature, Nelson *et al*. (1984) found that tiredness increases and productivity decreases with warmer temperatures. Hence, it might be more productive to have the temperatures lower than normal for places such as offices where the work is sedentary (Nelson *et al.*, 1984). Therefore, it is safe to conclude that it is more likely that productivity decreases as the temperature increases. It was also suggested that the perceived performance of the occupants was linked to the speed of the response of the building in an uncomfortable situation (Leaman and Bordass, 1999a).

The performance of a person to carry out a task with respect to the optimum performance depends on how aroused / alert he/she is (Parsons, 2003). Low arousal levels, caused for example by working on a boring activity, does not make the occupants alert enough for performance to be high, and vice versa for high arousal due to external sources, making the occupants over-excited and again their performance is decreased (McIntyre, 1980). Minimum arousal occurs when the temperature in the room is on the slightly warm side of the thermal neutral temperature, where one feels relaxed and drowsy. For maximum performance, the ambient temperature should be cool or warm (Figure 2.1).

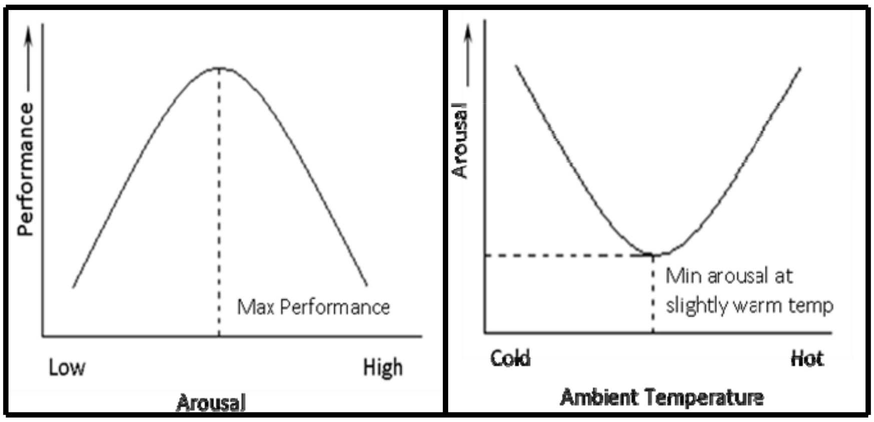

Figure 2.1: Relationship of arousal, performance and operative temperature.

Reference: Modified from McIntyre 1980.

Nelson *et al*. (1984) found that at warmer temperatures tiredness increases and productivity decreases. It was thus concluded that it might be more productive to have the temperatures lower than normal for places such as offices where the work is sedentary (Nelson *et al.*, 1984). A study performed in the Sacramento Municipal Utility District (SMUD) call centre in November in the late 1990s, showed that an increase of 1°C in air temperature (from 23°C to 24°C) decreased the performance of the workers by 2% (Heschong, 2006), confirming the findings of the study performed by Nelson *et al*. (1984).

2.1.6 Perceived Control, Thermal Comfort and Productivity

Research into the effects of personal control over environmental conditions suggests that productivity and health improve when people have more control (Baker and Steemers, 2000, Leaman and Bordass, 2006, Raja *et al.*, 2001, Vischer, 1989, Wyon and Wargocki, 2006b). Subjects who have more control over the environmental conditions of their workspace have a higher neutral temperature (warmer by 1.5°C over summer) than the ones that have no or minimal control even though both groups experienced the same thermal environment, with very similar clothing insulation and performed the same activities (Brager *et al.*, 2004). Leaman and Bordass (2006) commented that occupants are more likely to be forgiving of uncomfortable conditions if they feel they have more control over their environment even if the conditions are worse than if control was not available.

In a study on a group of offices at the University of Sydney, it was found that the conditions of the indoor environment were more acceptable if the occupants had some control, and it was also discovered that the occupants were feeling comfortable within the range of 20-25°C. (Lambert *et al.*, 1995). Having control in any building is good, however, as Leaman and Bordass (1999a) commented, control is more highly valued by the occupants if it is available when in an uncomfortable situation and does not affect the comfort of the others. The interaction of the occupants with their controls is more related to the indoor environment than with the external environment (Haldi and Robinson, 2008).

The perceived control affects productivity (Bordass *et al.*, 1993). The less perceived control, the more occupants are dissatisfied with the indoor environment, and hence the lower their productivity. In the PROBE study, people who perceived they were comfortable also felt they were healthy and productive in their office (Leaman and Bordass, 1999a). It was found that the difference in productivity between comfortable and uncomfortable occupants was 12.8%, which is considered a high percentage. Cellular offices have more control, especially over heating when compared to open-plan offices and ideally, occupants should be more productive (Leaman, 1995). Leaman explains that this does not mean design more cellular offices, but instead ensure that open-plan spaces have more perceived control.

Occupants value their freedom to control highly, and in order to keep a maximum number of occupants satisfied and avoid conflicts it is advised that no more than seven people at a time share offices (Doggart, 2006). Larger workgroups have lower perceived control over the various variables, as occupants start considering the wishes of other occupants and also the controls are more likely to be near a few people only (Leaman and Bordass, 1999b). Occupants feel they have low control over the temperature in their offices and even when they have thermostats they often do not know how to operate them, or they are not easily reachable, and even if they do change them they feel the changes are not as quick as in their own homes (Karjalainen, 2009). Barlow and Fiala (2007) showed that office occupants prefer to have more control over the centralized heating and ventilation systems instead of using individual items such as their own heaters or fans. Although controls are often available in the offices and near the occupants, occupants are not aware either how to use them or even that they can use them (Karjalainen and Koistinen, 2007).

The availability of control of the windows is regarded as the most preferred option of adaptive opportunities (Barlow and Fiala, 2007). In the UK there are three types of occupants in an office: the active (which make adjustments to the windows often), the passive (which are not using the windows at all) and the ones that make adjustments sometimes (Rijal *et al.*, 2007). People who say they use their windows often actually use them more actively than they believe (Rijal *et al.*, 2007). Occupants tend to use their controls such as windows more often if they perceive a higher control available to them (Yun *et al.*, 2008). Although a study in Finland showed that most occupants' response to discomfort in their offices is to change their clothing (dress less / more), using their window is quite popular if they are openable (Karjalainen and Koistinen, 2007). Nevertheless, a comfort model developed by the Centre for the Built Environment, (CBE), (Huizenga *et al.*, 2006), suggests that the closer an occupant is to a window the more likely their comfort is to be affected, due to localized discomfort. It was further suggested that the bigger the windows the more discomfort they were likely to cause.

Rijal *et al*. (2007) found that in the UK people opened their windows to decrease the indoor air temperature and to increase the air movement, and the windows tend to be left open until the occupants start to feel cold and this was approximately after a 4°C drop. The length of time that the windows are open depends on the length of time it takes for the cool external air to mix with the warm indoor air and then cool it enough for discomfort to occur. It also depends on the external temperature, and the windows tend to be opened when the indoor and outdoor temperatures are warm (Raja *et al.*, 2001, Rijal *et al.*, 2007).

Raja *et al*. (2001) have shown that in the UK if the external temperature was below 15°C, a few windows were opened in contrast to when the outdoor temperature was above 25°C, where almost all windows were open. At the end of September and the beginning of October, occupants in the UK offices suddenly stop opening the windows (on the first day that the outdoor temperature falls below 10°C) and since then there are less windows open from the end of October until the end of March, and again from the end of March to the beginning of April there is a sudden increase in the number of windows opened (Herkel *et al.*, 2008). They observed that small windows could be open even as long as 7 days without being closed at all, but other windows were rarely, if ever, opened. Fans in the NV buildings can be used in order to regulate the indoor temperature and increase the air velocity, but their use is related to the proximity of the occupants to them (Raja *et al.*, 2001).

2.1.7 Indoor Air Quality

Thermal comfort sensations are linked to the perceived indoor air quality (IAQ) of the occupants, as warm temperatures are often also perceived as stuffy whereas cold air is perceived as fresh but occupants are usually less tolerant of cold air (Fang *et al.*, 2004, Vischer, 1989). Temperature and humidity are inversely correlated to the perceived IAQ; as temperature and humidity of air increases, the perceived IAQ decreases for the same amount of air pollution (Fang *et al.*, 1998). It is suggested that for every 10% decrease in the number of people dissatisfied with the IAQ, there is an increase of 1.5% in performance of office work (Wargocki *et al.*, 2000). However, a poor IAQ can reduce the performance of the office workers by 6-9% (Wyon, 2004).

Routlet (2007) has suggested that the airflow rates providing good indoor air quality and a comfortable indoor environment are not necessarily the same. Increasing the ventilation rate from 3.5 ls^{-1} to 10 ls^{-1} per person increases the initial perceived IAQ (Fang *et al.*, 2004). Further work on HVAC buildings indicates that productivity increases as ventilation rates increase (Seppänen *et al.*, 2006), and the frequency of SBS symptoms decreases (Fisk *et al.*, 2009).

During the heating period, one of the main sources of contamination of the indoor air is the occupants. The air in a room is regarded as a high quality if the indoor CO_2 levels are less than 400ppm above the level of the outdoor CO_2 concentration, as medium quality if levels lie between 400 and 600ppm above, and of moderate quality if the levels are between 600ppm and 1000ppm above (BS EN 13779, 2007). Rooms with indoor CO_2 levels higher than 1000ppm above the outdoor concentration are regarded as having low indoor air quality (BS EN 13779, 2007). An airflow rate of 22m^3/h per person makes the CO_2 levels rise indoors to approximately 1000ppm higher than the outside level, and 54m^3/h per person makes the CO_2 level approximately 400ppm higher inside than outside (Roulet, 2007). In a cross-sectional study conducted in nine buildings with open-plan offices, it was suggested that the CO_2 level in offices should be below the suggested ASHRAE recommended levels of 1000ppm, and in fact they should not exceed 650ppm (Newsham *et al.*, 2008).

2.1.8 Clothing and Thermal Comfort

Although clothing cannot be controlled in studies, it is one of the major factors affecting the responses of the subjects in the field studies (Humphreys, 1976). Clothes are one of the necessities to help maintain comfort, but in some cases fashion is superior to comfort, and hence people might under-dress (Barlow and Fiala, 2007, McIntyre, 1980). Moreover, although low indoor air temperatures (15°C) have been found to be comfortable in earlier studies, such temperatures would require a lot of clothing compared to the current customs of the UK (Humphreys and Nicol, 1995).

Parsons (2002) suggested that people adjust their clothes in order to tolerate a certain environment, but the reduction of clothes in a warm environment depends on the modesty and acceptance of the dressing habits. However, office occupants tend not to change their clothing throughout the day (Barlow and Fiala, 2007), which is also supported by the findings of the Passive Cooling (PASCOOL) project. In the PASCOOL project, which was funded by the European Union to look into comfortable free-running buildings, the occupants were completing questionnaires on an hourly basis (Baker and Standeven, 1996). It was concluded that occupants in offices do not use their clothing to achieve thermal comfort.

In a study in Japan, it was suggested that the clothing of the occupants of NV office buildings which are free-run during the summer period varies in accordance with the outdoor temperature like the indoor temperatures (Goto *et al.*, 2007), which is also the case for the majority of the European buildings (Nicol and Humphreys, 2007). The outdoor morning temperature (6am) highly influences the clothing occupants chose to wear for NV buildings (De Carli *et al.*, 2007). The indoor air temperature has minimal influence on their choice of dress in the morning, but becomes more influential on their change of clothing throughout the day, provided that they are allowed to change their clothing (depends on office policies) (De Carli *et al.*, 2007). In the PASCOOL project, 75% of the occupants of the offices were influenced by the morning thermal conditions on what to wear, as it affected their expectations (Baker and Standeven, 1996).

A study comparing casual and formal clothing in an air-conditioned office in Sydney has shown that people's choice of 'mufti-clothing' is influenced by the outdoor temperature and does not correlate with the indoor temperature. However, on the formal days, the strict dress code resulted in no correlation with the indoor and outdoor temperatures (Morgan and de Dear, 2003). Consequently, strict dress codes act negatively on the thermal comfort of occupants and hence on their performance (Nicol, 2008). In 2005 the Japanese Government introduced a campaign called the Cool Biz, where office occupants are encouraged to wear more relaxed dress codes over summer, in an attempt to make higher indoor air temperatures over summer comfortable (Cool Biz, 2005). When office occupants do not wear ties or jackets, the body temperature is decreased by up to 2°C (Lorenzo *et al.*, 2008) and hence higher indoor air temperatures can be maintained.

It is vital to have more freedom in the choice of clothing and to allow the workforce to wear cool clothes in summer and warm clothes in winter (Nicol, 2008). One must make more adjustments in their clothing if they are tired, as fatigue has a negative effect on the perception of the environmental conditions, and hence the more tired one is the more effect draughts and temperatures will have on them (Griefahn and Kunemund, 2001). Clothing insulation values based on the garments occupants wear can be calculated using the BS EN ISO 7730 (2005).

2.2 Naturally Ventilated Buildings

Natural ventilation is required in buildings for various reasons such as controlling the indoor temperature, to assist in the cooling of the body of the occupants and hence assist in their comfort or to ensure good indoor air quality (Maldonado, 2002). The reasons for good ventilation are more than just to maintain a comfortable temperature inside the room. Good ventilation eliminates bad odours in spaces and reduces indoor CO_2 levels (Roulet, 2007). If a building has been designed properly for natural ventilation, there will also be good adaptive opportunities for the occupants (CIBSE, 2005b).

It is suggested by Lush (1992) that in most UK buildings that are heated and naturally ventilated, the way the air exchange is provided and the temperature controlled is via infiltration and manually opening the windows. In single-occupancy offices this is ideal, but in multi-occupancy offices what is deemed good ventilation varies from person to person (Lush, 1992). Draughts are caused when the air-exchange inside is large and the air-velocities are larger than desired. Draughts can cause a lot of discomfort depending on their strength, especially if they move papers around (Maldonado, 2002).

2.2.1 Natural Ventilation Strategies

When windows (next to each other) or doors are open only on one of the sides of the ventilated space, this is referred to as is single-sided ventilation (CIBSE, 2005b). The ventilation rate is lower and hence the air travels for shorter distances. It is suggested by CIBSE (2005b) that the length of the office should be less than or equal to 2 times the height of the office for ventilation to be effective in such circumstances. When there are two openings at different heights on one of the sides of the ventilated space, e.g. a sash window opens at the bottom and top, it is known as double-opening single-sided ventilation (CIBSE, 2005b). The suggested length of the enclosure in this case should be less than or equal to 2.5 times the height of the building (CIBSE, 2005b). There are different types of windows, and each one affects the pattern and velocity of the incoming air differently, and consequently impacts the thermal comfort of the occupants depending on how the air arrives in the occupied zones (Heiselberg *et al.*, 2001).

2.2.2 Ventilation Rates and Indoor Relative Humidity

Indoor humidity levels are affected by ventilation rates with the higher ventilation reducing the humidity (Seppänen and Fisk, 2004). Relative humidity (RH), defined by HSE (1992) as the ratio between the actual water vapour the air holds and the maximum it can hold at that specific temperature, is the most popular measure of indoor humidity levels in thermal comfort studies (Nicol, 2004). It is recommended that RH should be between 40% and 70% if it is to have minimal effect on the thermal comfort of the occupants (HSE, 2007). This range is popular in offices (Nicol, 2004), however, Vischer (1989) suggested RH for indoor environment of offices to be between 40% and 60%.

High levels of humidity make the occupants feel warmer, especially if the air-speed is low (Monash University, 1999). If RH is high, it will affect the evaporation of sweat from the occupants (Nicol, 2004). RH less than 40% affects the health of the occupants by irritating the eyes and the skin, drying the throat etc. as well causing electrostatic shocks (EPA, 1997). RH above 50% may also start increasing SBS symptoms (Seppänen and Fisk, 2004). High RH (e.g.

>70%) makes the temperature range in which the occupants feel comfortable narrower (Haves, 1992). Buildings which are only heated or cooled do not have a control for humidity (Indoor Health Products Inc., 2007), unlike fully air-conditioned ones. However, weather conditions in the UK are such that the humidity usually lies in the region suggested above unless it is very cold or very hot (Lush, 1992).

Ventilation is not only used to control the indoor thermal environment and humidity, but also to control air speed. For example, increasing the air speed reduces the effect of thermal stress in high temperatures on humans (Seppänen and Fisk, 2004). Therefore, although a lightweight building is more likely to heat up, the thermal stress on the occupants could be reduced through proper ventilation.

2.3 Building Fabric and Thermal Mass

The building fabric, consisting of walls, floors, windows, doors and roofs, provides shelter for the occupants and affects the building's indoor environmental conditions (CLEAR, 2004). The building fabric affects the flow of energy between the interior of the building and the outdoor climate (CLEAR, 2004). Various materials, each having a different thermal conductance, when connected together (either in parallel or in series) make the building fabric (Haasea and Amatob, 2009). The overall thermal performance of the building fabric depends on the individual thermal conductance of the various materials (CLEAR, 2004).

The building fabric has a great influence on the amount of energy used in the building, in terms of both the embodied energy and the energy lost through it (Haasea and Amatob, 2009). The ability of the materials to absorb, store and release thermal energy is known as thermal mass (SEA, 2008). High thermal mass buildings, also known as heavyweight buildings, are more thermally comfortable over summer when compared to identical low thermal mass (lightweight) buildings, as lower indoor air temperatures can be achieved according to Shaviv *et al.,* (2001).

2.3.1 Thermal Mass Theory

Ward (2004) describes high thermal mass buildings as maintaining almost a constant indoor air temperature, despite the activities taking place inside the building or the external temperature. The higher the density of a material, e.g. concrete, the greater its thermal conductivity, and hence the higher its thermal mass (Ward, 2004). Consequently, these type of buildings are never extremely hot in summer or cold in winter, as the materials absorb the heat and release it at a later time (which varies from a few hours to a few years) (Ward, 2004).

Heat is absorbed from the surface of the structure during day-time from solar radiation (shortwave radiation), from radiation from surfaces and other emitters (longwave radiation) and from convection with the air (Steemers, 2006). Heat is stored in the materials and eventually the temperature of the surfaces rise. Heat is then transferred between the various surfaces due to air convection or longwave radiation. The more exposed the surfaces of a building are the better their ability to absorb and release heat (Ward, 2004). The extent to which the structure responds to these thermal inputs is known as thermal response (Steemers, 2006) and is affected by the thickness of construction, thermal properties of the construction, surface finishes and the type of thermal input (CIBSE, 2006). A heavyweight building responds slowly to heat gains (McMullan, 2002) and has a high thermal response factor[†] (f_r). In order to calculate the thermal response factor the surface areas, thermal transmittance (U-value) and thermal admittance (Y-value) of the surfaces that heat flows through should be known as well as the ventilation conductance. Providing explanations of all the above parameters is beyond the scope of this thesis and detailed information can be obtained in CIBSE Guide A (2006) and BS EN ISO 17386 (2007). In this thesis only the terms U-value and Y-value are explained (Section 2.3.2).

The heat capacity (C_m) of a structure can be used as an indication of its thermal response (Steemers, 2006). Heat capacity can be defined as the maximum change in the heat stored within a material for half of its sinusoidal cycle (assuming that it follows a 24 hour sinusoidal temperature variation)[‡] (BS EN ISO 13786, 2007, CIBSE, 2006).

The rate of decrease of the peak temperature depends on the thermal mass of the building (Ward, 2004). Materials with higher mass can store more energy and hence can keep heat over a longer time-span resulting in heavyweight buildings having lower indoor air temperatures (Figure 2.2) and having a much lower risk of overheating when compared to lightweight buildings (Saulles, 2005).

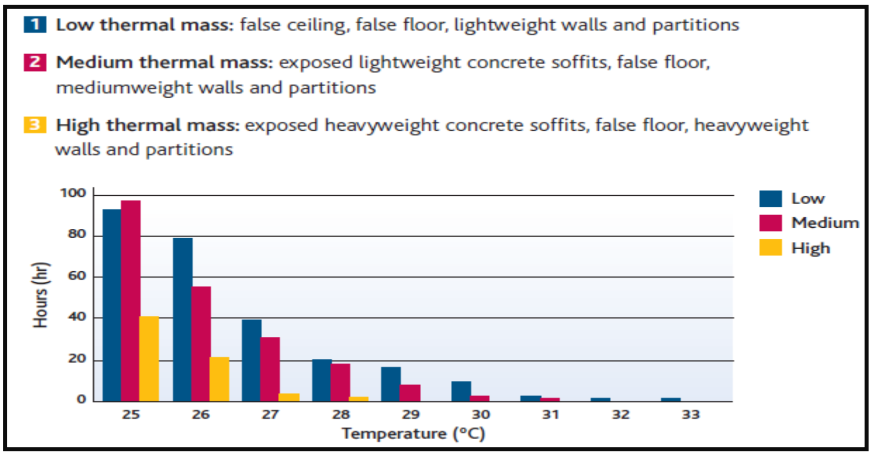

Figure 2.2: Comparison of indoor air temperatures for three naturally ventilated offices of different thermal mass in London.

Reference: (Saulles, 2005).

Further, the higher the thermal mass, the later the peak of indoor temperatures compared to the outdoor peak temperatures. In an office environment for example, high thermal mass

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[†] Thermal response factor (CIBSE 2006):

$$f_r = \frac{\sum (A\,Y) + C_v}{\sum (A\,U) + C_v}$$

where A = surface area (m^2) $\quad$ C_v = ventilation conductance (WK^{-1})
Y = thermal admittance ($Wm^{-2}K^{-1}$) $\quad$ U = thermal transmittance ($Wm^{-2}K^{-1}$)

if $f_r > 4$ → slow response building, i.e. heavyweight building
$f_r \leq 4$ → fast response building, i.e. lightweight building

[‡] Details on the calculation of heat capacity can be found in BS EN ISO 13786 (2007).

buildings can have the peak indoor air temperature delayed by up to six hours from the outdoor peak temperature (Saulles, 2005).

2.3.2 Parameters Affecting the Response of Surfaces

U-Value

The thermal transmittance (U-value) is one of the key factors determining the heat lost or gained through the building fabric (CIBSE, 2006). It is defined as the rate of heat flow per unit area of material(s), per 1°C difference between two environments the components of the structure are exposed to (CIBSE, 2006, CLEAR, 2004). The U-value is the inverse of the thermal resistance (R-value) of materials. Thermal resistance of a material is a function of its thermal resistivity, which is defined as the resistance of the material to heat flow, and the thickness of the material (CLEAR, 2004).

Baker (2009) points out that even the best performance windows have a U-value of at least five times higher than a typical insulated solid element (such as a wall). When a window is in the vicinity of direct sunlight the effect of the amount of irradiance that passes through it is forty times greater than the effect of a 20°C difference between the indoor and outdoor air temperature through a wall (U = 0.5W/m^2).

Although two buildings can have a different thermal mass e.g. concrete and timber, they can have very similar U- and R-values[§]. The heat flow through the two materials is the same, provided that they are under the same conditions (Sustainable concrete, 2006, Ward, 2004). However, the time it takes the heavyweight material to reach its peak temperature is longer than the time it takes the lightweight material to reach its maximum (Ward, 2004).

Y-Value

The thermal admittance (*Y-value*) is defined as the 'rate of heat flow between the internal surface of the structure and the environmental temperature in the space for each degree of deviation of the space temperature about its mean value' (CIBSE, 2006). The greater the density of the material (heavyweight), the larger its admittance, and therefore the smaller the temperature swings (BS EN ISO 13786, 2007).

[§] *U*-value is calculated as follows:

$$U = \frac{1}{(R_{si} + R_1 + R_2 + \ldots R_n + R_a + R_{se})}$$

Where

R_{si} = internal surface resistance
R_{se} = external surface resistance
R_1, R_2, R_n = thermal resistance of components 1,2 up to n
R_a = air space thermal resistance

R-value is calculated as follows:

$$R = \frac{d}{\lambda}$$

Where

d = thickness of material
λ = thermal conductivity

2.3.3 Factors Influencing the Effectiveness of Thermal Mass

Through simulations, Shaviv *et al*. (2001) found that the reduction of the indoor air temperature during the summer period depends on the thermal mass of the buildings (whether heavyweight or lightweight) but also on three other parameters: (a) the amount of exposed thermal mass, (b) the amount of night ventilation available to the building, (c) the daily temperature swing of the area. Further, it was suggested by Ward (2004) that if the thermal mass of a building is exposed then it is expected that the indoor air temperature will be between 2-4°C cooler at the peak temperature periods. Facade colour affects the amount of reflectance of solar radiation, with darker facade colours having higher maximum indoor air temperatures than lighter ones, and hence greater diurnal swings (Goulding *et al.*, 1993).

Other factors that affect indoor air temperatures are the angle at which the windows are placed (Goulding *et al.*, 1993). Vertical windows have a smaller exposed area to direct sunlight over summer than horizontal ones. In the present study, all windows are vertical. The size of the window also affects the amount of solar radiation entering a space. The solar radiation increases the radiant temperature, and the surfaces and materials in the offices absorb it and then increase the air temperature of the spaces (Ward, 2004). Further, large glazed areas are more prone to causing heat discomfort to occupants sitting near the windows (Ward, 2004). Indoor blinds do not stop the solar radiation from getting in the room. Instead, it is redirected on to other surfaces and only delays the increase in the air temperature (Ward, 2004).

2.4 Facade Orientation

A chamber study for spring time in Hong Kong, confirmed that south-facing lightweight facades are significantly warmer than north-facing ones (Cheng *et al.*, 2005). Differences between the two orientations reached 16°C in some cases. Further, the east-facing facades reached their peak temperature in the morning whereas the west-facing in the evening, which is similar to the findings from the simulation of a sunspace located at a latitude of 51°N performed by Goulding et al. (1993) (Figure 2.3).

In all cases, the outdoor air temperature was much lower than the resulting indoor air temperature (up to 20°C). When he performed the same study but using a high thermal mass building the indoor temperatures were very similar regardless of the orientation, except the west-facing facades, which were much warmer, and the peak was reached during the late afternoon. Although for the lightweight building the indoor air temperature was lower than the outdoor temperature during the night-time, for the heavyweight building it was consistently higher than the outdoor.

Haasea and Amatob (2009) suggested that the optimal facing orientation for many buildings is north-south (with the shorter facades facing in the east and west direction). It was further mentioned that an optimal orientation for winter does not necessarily correspond to the same optimal orientation for the summer. Goulding *et al*. (1993) commented that when comparing a south-facing building side to the other orientation, the south-facing receives higher solar radiation over winter but less over summer. West-facing windows can encounter problems with overheating during summer if they are not protected from direct sunlight (Goulding *et al.*, 1993). Nevertheless, when comparing west- and east-facing spaces, and south-west and south-east facing spaces on an annual basis, they tend to have similar solar gains and hence will have similar indoor temperatures.

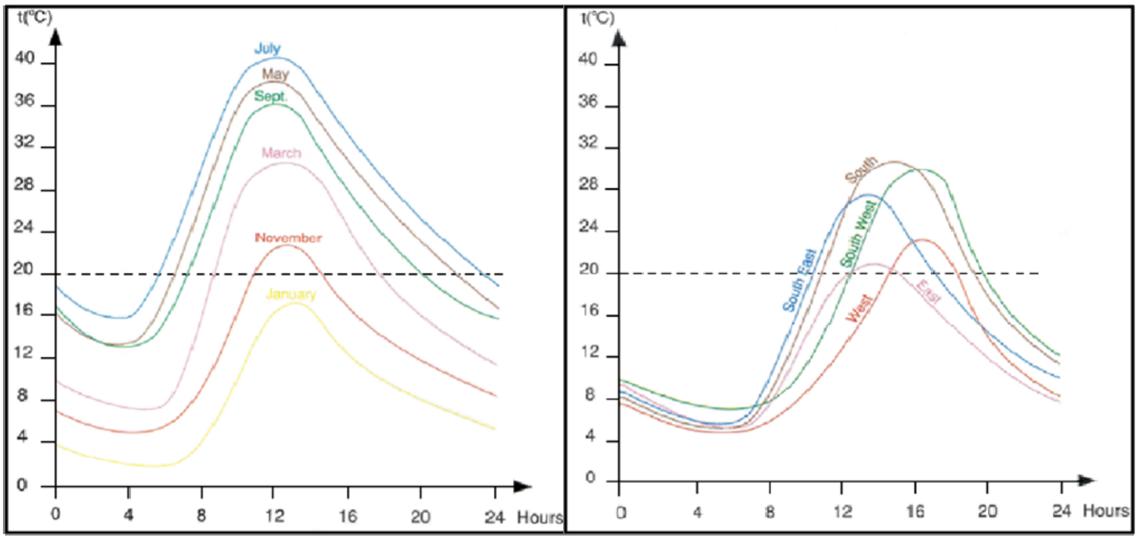

Figure 2.3: The left figure shows the indoor air temperatures over different months for the same building. The right figure shows the indoor air temperature for March for spaces located in the same building but having different orientations.

Reference: (Goulding et al., 1993).

2.5 Building Regulations

Prior to 1965 there were no building regulations in the UK regarding minimum standards of insulation (Waters, 2003). Even then, the first standards were incorporated only for the dwelling sector. Part L of the Building Regulations was first introduced in 1970 with the aim of conserving fuel. It has since then been modified several times with its objectives changing to reduce CO_2 emissions which cause climate change (1990), and to make buildings more sustainable overall (2006) (Wright, 2008). Suggested U-values for walls, roofs and floors are constantly modified - almost every decade, being stricter each time, with some values more than halving the initial 1970 value.

In 2003, the EU Energy Performance in Buildings Directive introduced the Energy Performance Certificates (EPC) which show the energy efficiency of buildings. Display Energy Certificates (DEC) illustrate the actual energy usage of buildings that have a floor area of more than 1000m^2, such as the university buildings studied in this case, and are compulsory since 2008 (Communities & Local Gov., 2008). EPCs and DECs compare the energy performance of similar style buildings. The buildings studied as case studies are expected to be more leaky and have lower U-values when compared to similar building constructed in this decade. However, refurbishing non-domestic buildings is usually better than rebuilding them both in terms of energy consumption and economically (Baker, 2009).

SUMMARY

Office occupants tend to dislike sudden temperature changes, fluctuations and draughts. The thermal comfort of the occupants depends on conditions they cannot select due to the construction of the building such as the thermal mass, but also on conditions they can adjust their clothing. This chapter showed the importance of creating buildings that are thermally comfortable and the lack of strict temperature office standards in the UK. The next chapter introduces the case study buildings.

Chapter 3

BUILDING DESCRIPTION

The University of Bath (Figure 3.1) located in south-west England, commenced its construction in the mid-1960s. The site usually has a south-west prevailing wind (but sometimes north-east), with the coldest months being January and February (average maximum of 7°C) and the warmest months being July and August (average maximum of 20°C) (Met Office, 2009b).

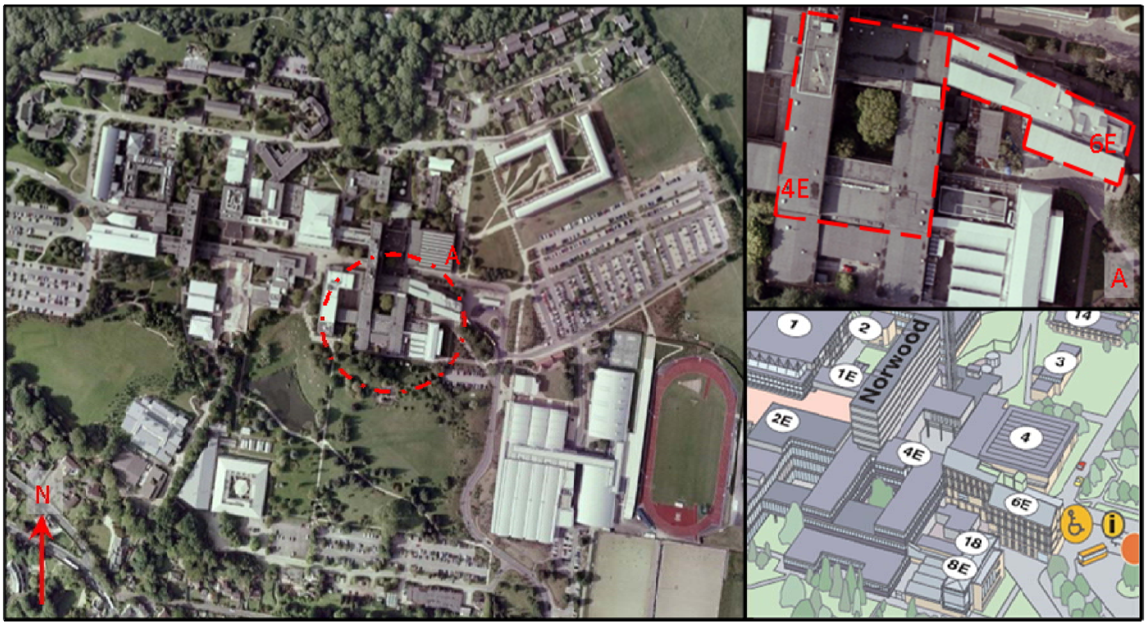

Figure 3.1: University of Bath and the two buildings used as case studies (4E and 6E).

Source: The satellite pictures have been modified from Google Earth and the sketch of the two buildings was obtained from the University of Bath.

The two buildings chosen as case studies for this thesis are 4 East (4E), a lightweight building constructed in the 1970s, and 6 East (6E), a heavyweight building constructed in the 1980s (Figure 3.1). Contrary to expectations, it appears that the period of construction alone has a weak correlation with the total energy consumed in higher educational buildings (Ward *et al.*, 2008). Hence, significant differences in energy consumption are expected to be due to different operations of the buildings, rather than due to differences in age.

A primary reason for choosing these two buildings is the difference in their thermal mass. Further, most of the academic staff and research students are known by the author, and hence a high response rate was obtained in the subjective data collection. More information regarding these two buildings and their offices are included in this chapter.

3.1 Lightweight Building

The 4E building (Figure 3.2) is mainly occupied by staff from the Department of Mechanical Engineering (ME), and partly by staff from the Department of Architecture and Civil Engineering (ACE). The building has an energy efficiency rating of 111 (E) on the DEC, which is below the typical value for similar buildings (100 (D))

Figure 3.2: Exterior and interior images of the 4E building.

3.1.1 BUILDING DESCRIPTION

Although construction drawings of the building were obtained from the Department of Estates, information on the construction of the second and third floor could not be obtained. Consequently, assumptions were made about the construction of the internal and external walls, floors and ceilings of the offices.

The offices located in this building all had suspended ceiling (240 mm concrete slab, followed by a 100 mm long steel beam, 10 mm of asbestolux and then 300 x 300 mm ceiling tiles of 19 mm thickness which are kept in place with sheet-metal tees). The floor consisted of slab covered with needle-punched carpet. The internal walls were made of 20 mm plasterboard, 50 mm air cavity and 20 mm plasterboard. The internal walls were all painted white.

The external walls are made of (from outdoor to indoor) 20 mm plasterboard (λ = 0.16 $Wm^{-1}K^{-1}$, ρ = 950 kgm^{-3}, c = 840 $Jkg^{-1}K^{-1}$)[*], 50 x 120 mm wood stud (λ = 0.15 $Wm^{-1}K^{-1}$) at 600 mm c/c or 120 mm air cavity (λ = 0.18 $Wm^{-1}K^{-1}$) and 20 mm plasterboard with finishing (λ = 0.16 $Wm^{-1}K^{-1}$, ρ = 950 kgm^{-3}, c = 840 $Jkg^{-1}K^{-1}$). The ratio of glass (single-glazed, λ = 1.1 $Wm^{-1}K^{-1}$) to the external wall for each office is 50%. Consequently, the average U-value of the external wall is estimated to be 3.33 $Wm^{-2}K^{-1}$.

The heat capacity of the external wall is estimated to be 31.9 $kJm^{-2}K^{-1}$ (δ = 0.074 m, hence C_m = 2 x 15.96 $kJm^{-2}K^{-1}$)[†]. This value suggests that the building is a very lightweight one (C_m << 80 $kJm^{-2}K^{-1}$) (BS EN ISO 13790, 2008).

A third of the total glazed area is openable windows (usually two windows) and are made of clear glass (single-glazing), whereas two-thirds of the glazed area is fixed glass with a frosty pattern styling, located at the top of the wall. The windows are top-hung, and are located at sitting height. All windows in the vicinity of direct sunlight have internal blinds.

The offices are heated via radiators in winter and each radiator has a thermostatic radiator valve (TRV) to provide the occupants with control over the temperature of the radiator. The heating of the university is switched on in late September and switched off in June (Department of Estates, 2010). On weekdays the heating is on from 07.30 to 19.00, and is set to maintain 19°C. However there is only one sensor for the building located in a corridor on the second floor and hence it does not give a representative view of the temperature in the offices on floor three. The pipes transferring warm water for the heating are not visible as they are inside the external wall. Over the weekends the heating is off. However, there is a frost protection setting for the pipes that is engaged if the temperature goes below 10°C and is switched off when the temperature reaches 12°C.

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[*] The thermal conductivity values (λ) of each material are based on the values suggested in the book written by Ward, I. (2004), which is based on the 2000 England and Wales Building Regulations Part L and CIBSE Guide A (2006). The other values are based on CIBSE Guide A (2006).

[†] Heat capacity was estimated using BS EN ISO 13786 (2007).

Assuming period of variation, T = 24 hours (86 400s), the penetration depth, δ, was calculated using equation $\delta = \sqrt{\frac{\lambda T}{\pi \rho c}}$.

Since $\delta > ½(d)$ for the first layer of the building component, heat capacity equation $C_m = d.\rho.c$

3.1.2 Office Selection

The single-occupancy offices on the second floor are located around a courtyard, with a tree in the middle (Figures 3.1 and 3.3). Most of the offices occupied by the academics and research students are located on the third floor, the floor chosen for monitoring (Figure 3.3). The second floor (entrance level) is occupied partly by academic staff and partly by administrative staff, whereas the first floor (basement) is dedicated to laboratories and workshops.

The offices facing west are mostly occupied by ACE staff, whereas the ME staff are located on the south and mainly on the west of the building. There are no single-occupancy offices facing north.

Figure 3.3: Plan of the floor monitored in 4E.

Note: Red represents single-occupancy offices, blue represents multi-occupancy offices and green represents the other offices on that floor. The plan is NOT to scale.

Table 3.1 gives details of the offices selected from the 4E building, including information on the gender of the people, the number of people occupying the room and the monitoring period. Table 3.2 shows the dimensions of the monitored spaces and their windows. The offices in this building are 3m high, and hence in order to have effective ventilation, the length of the offices should be less than or equal to 6m. This means that one of the multi-occupancy rooms (NL1 – Table 3.2) is highly likely to have a problem with its indoor air quality if the door is shut.

Table 3.1: General information on the offices chosen for the study in 4E.

Office	Orientation	Number of occupants	Gender	Monitoring Date(s)
WL1	West	1	M	20/03/09 – 25/03/09 06/05/09 – 13/05/09 22/06/09 – 03/07/09 (HW)
WL2	West	1	M	23/03/09 – 25/03/09
WL3	West	1	M	14/10/08 – 01/12/08 28/01/09 – 09/02/09 (CS)
WL4	West	1	M	14/10/08 – 01/12/08 28/01/09 – 09/02/09 (CS)
WL5	West	1	F	20/03/09 – 20/03/09 06/05/09 – 13/05/09
SL1	South	1	F	22/06/09 – 03/07/09 (HW)
SL2	South	1	M	07/07/09 – 14/07/09
SL3	South	1	M	07/07/09 – 14/07/09
SL4	South	1	M	07/07/09 – 14/07/09
SL5	South	1-3 (P)	M	22/06/09 – 03/07/09 (HW)
EL1	East	1	F	22/06/09 – 03/07/09 (HW)
EL2	East	1	M	07/07/09 – 14/07/09
NL1	North	3-7 (P)	M & F	22/06/09 – 03/07/09 (HW)

Note: (P) postgraduate rooms, (HW) heat-wave period, (CS) cold-snap period.

Notation: [orientation][lightweight / heavyweight][office number]

Table 3.2: Information on the dimensions of the offices chosen for the study in 4E.

Office	Number of openable windows	% glazed area of external wall	Dimensions of the room (precision: ±0.1 m) (width x length x height)
WL1	2	50	2.3 x 3.4 x 3.0 m
WL2	2	50	2.3 x 3.4 x 3.0 m
WL3	2	50	2.3 x 3.4 x 3.0 m
WL4	2	50	2.3 x 3.4 x 3.0 m
WL5	2	50	2.3 x 3.4 x 3.0 m
SL1	2	50	2.3 x 3.4 x 3.0 m
SL2	2	50	2.3 x 3.4 x 3.0 m
SL3	2	50	3.4 x 3.4 x 3.0 m
SL4	4	50	3.4 x 3.4 x 3.0 m
SL5	4	50	3.4 x 4.5 x 3.0 m
EL1	2	50	2.3 x 3.4 x 3.0 m
EL2	2	50	2.3 x 3.4 x 3.0 m
NL1	2	50	3.5 x 8.9 x 3.0 m

3.2 Heavyweight Building

The chosen heavyweight building (6E) (Figure 3.4) is solely occupied by the ACE Department. Offices inhabited by lecturers are distributed on all three floors of the building with the majority being on the top floor. Similar to the lightweight building, the head of the department and senior academic staff are located on the bottom floor, and hence it was decided not to include those offices in the study. Further, their offices are larger than the average offices of the building and this would add another variable to the study.

Figure 3.4: Construction details of 6E (internal and external).

3.2.1 Building Description

The building is mostly constructed from concrete, and has a large exposed mass inside various spaces in the building and in the offices. The building has an energy efficiency rating of 94 on the DEC, which suggests that it is as energy efficient as a typical building of this style, and more energy efficient than the 4E building.

Information on the construction of the 6E building was obtained through the Department of Estates of the University of Bath and through a published article in Architect's Journal (Turnbull, 1988). Internal walls were constructed of 90 mm thick concrete blocks, and some are covered by plaster. The building has a high thermal mass and many concrete walls which are unpainted. The floors of the offices have been constructed with 300 mm concrete slab, 35 mm screed and needle-punched carpet. The roof (affecting only offices on the top floor), is made of stainless steel sheet, 19 mm plywood, 50 x 200 mm timber joist, 100 mm insulation, softwood plate and steel beam (356 x 171 x 57 mm).

The external wall of the building was constructed (from outdoor to indoor) from 90mm thick Doulting limestone (λ = 1.7 $Wm^{-1}K^{-1}$, ρ = 2261 kgm^{-3}, c = 737 $Jkg^{-1}K$), 50mm thick expanded polystyrene insulation (λ = 0.04 $Wm^{-1}K^{-1}$, ρ = 100 kgm^{-3}, c = 750 $Jkg^{-1}K$) and 90mm thick concrete blocks (λ = 1.93 $Wm^{-1}K^{-1}$, ρ = 2300 kgm^{-3}, c = 840 $Jkg^{-1}K$), and in some instances the concrete was covered by plaster 13 mm thick (λ = 0.57 $Wm^{-1}K^{-1}$, ρ = 1200 kgm^{-3}, c = 840 $Jkg^{-1}K$). The proportion of glazed area to the external wall varies amongst the different types of office (Table 3.3). The estimated U-value of the external wall with 25% glass is estimated as 1.72 $Wm^{-2}K^{-1}$ (without the glass, the U-value of the external wall is 0.649 $Wm^{-2}K^{-1}$). The heat capacity of the external wall is estimated to be 340 $kJm^{-2}K^{-1}$ [‡], which is a heavyweight / very heavyweight building (260-370 $kJm^{-2}K^{-1}$ [§]).

As the colour of the external facade of this buildings is pale beige, it is expected that it will also have an impact on the indoor air temperatures as more solar radiation will be reflected than from the darker coloured facade of 4E (Goulding *et al.*, 1993).

All the windows are double-glazed with an aluminium frame. The sash windows (Figure 3.4) offer the advantage of opening without requiring a significant amount of space (Roulet, 2007). However, they are generally less air tight than the top-hung ones (Roulet, 2007). Apart from one of the two postgraduate rooms (SH2 – Table 3.3) which has windows in two directions, the other offices have single-sided ventilation if the door is closed, but with opportunity of double-opening – i.e. opening the bottom and top part of the window. The south-facing single occupancy office has an overhanging roof (located on the top roof – marked as A on Figure 3.4), which stops direct solar radiation entering the office.

Similarly to the lightweight building, the offices are heated using radiators with TRVs for occupants to control their temperatures. The heating for the building is switched on in September and switched off in July. The building is divided into two zones; north and south. For the north zone the heating is set to maintain 20°C and runs from 06.30 to 19.00, and similarly in the south zone, although it commences at 07.00. Over the weekend the heating is off. Unlike in the lightweight building, the pipes are not covered inside the walls but instead are attached on the internal walls. This affects the indoor air temperatures during winter as even when the heating is turned to the lowest setting via the TRV, there is always heat radiated from pipes in the room.

3.2.2 Office Selection

Ideally, all offices should have been chosen from the intermediate floors, and not from the top floor of the building, as heat is lost and gained from the exposed ceiling (roof). However, this was not possible as a substantial number of single-occupancy offices are found on the fourth floor (top), and only a few on the third floor (middle). Figure 3.5 shows the plans of the two 6E floors where offices were chosen for monitoring. Tables 3.3 and 3.4 give details of the offices selected.

[‡] Using simplified equation $C_m = d.\rho.c$

[§] From Table 12 of BS EN ISO 13790 (2008).

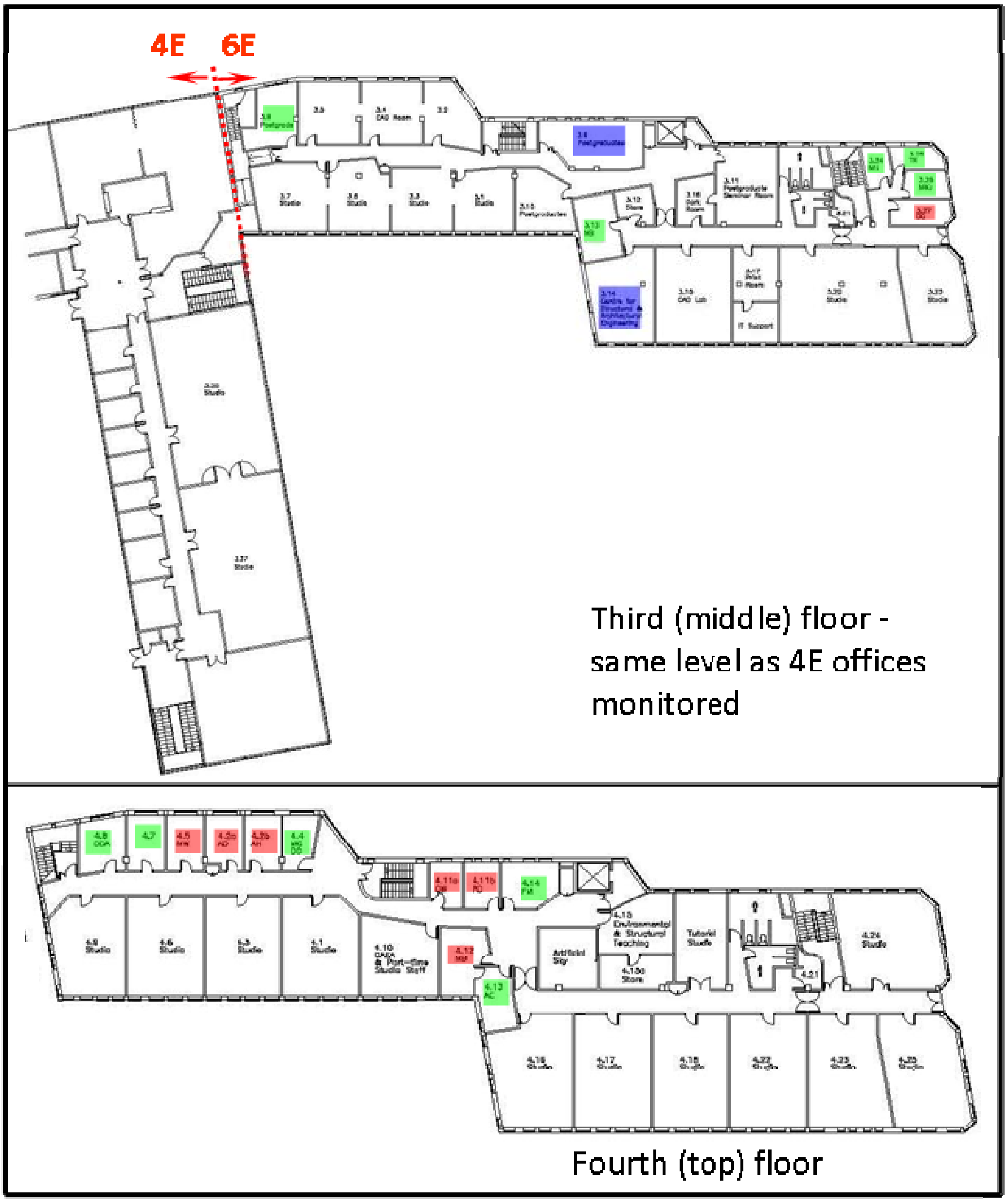


Figure 3.5: Plans of the floors monitored in 6E.

Note: Red represents single-occupancy offices, blue represents multi-occupancy offices and green represents the other offices on that floor. The plan is NOT to scale.

Table 3.3: General information on the offices chosen for the study in 6E.

Office	Orientation	Number of occupants	Gender	Monitoring date(s)
NH1	North	1	M	14/10/08 – 01/12/08 28/01/09 – 09/02/09
NH2	North	1	M	14/10/08 – 01/12/08 28/01/09 – 09/02/09 22/06/09 – 03/07/09 (HW)
NH3	North	1	M	26/03/09 – 02/04/09
NH4	North	1	M	28/04/09 – 01/05/09 07/07/09 – 14/07/09
NH5	North	1	F	26/03/09 – 27/03/09 28/04/09 –06/05/09
NH6	North	3-8 (P)	M & F	04/12/08 – 08/12/08 09/02/09 – 19/02/09 (CS) 22/06/09 – 03/07/09 (HW)
SH1	South	1	M	07/07/09 – 14/07/09
SH2	South and West	6-9 (P)	M & F	04/12/08 – 08/12/08 09/02/09 – 19/02/09 (CS) 22/06/09 – 03/07/09 (HW)
EH1	East	1	M	22/06/09 – 03/07/09 (HW)

Note: (P) postgraduate rooms, (HW) heat-wave period, (CS) cold snap period.

Table 3.4: Information on the dimensions of the offices chosen for the study in 6E.

Office	Number of openable windows	% glazed area of external wall	Dimensions of the room (precision: ±0.1m) (width x length x height)
NH1	2	25	2.6 x 4.3 x 2.8 m
NH2	2	25	2.6 x 4.3 x 2.8 m
NH3	2	25	2.6 x 4.3 x 2.8 m
NH4	2	25	3.0 x 3.4 x 2.8 m
NH5	2	20	2.0 x 3.4 x 2.8 m
NH6	2 and 4 half the size of the other 2	30	4.3 x 9.0 x 3.0 m
SH1	2	25	2.3 x 3.4 x 3.5 m
SH2	2 (west facing) and 4 (south facing)	10 (west) 40 (south)	5.6 x 8.6 x 3.0 m
EH1	2	25	2.4 x 5.4 x 3.0 m

3.3 Electrical Equipment in Offices

The electrical equipment in each office was recorded on the day the monitoring of each office commenced. All single-occupancy offices had approximately the same electrical equipment in their office; a desktop computer and in most cases a desk lamp and a small printer. In some cases occupants also used their laptops, but this was not on a daily basis. Further, the occupants of WL5 and NH3 had two desktop computers in their room, however, occupant WL5 only had one switched on at a time. Some people had their own portable heaters during winter and personal fans during summer (Table 3.5). Therefore, the contribution of the electrical equipment to the internal heat gains is expected to be approximately the same for all the single-occupancy offices, unless a portable heater / fan was used in which case it was noted during the survey.

Table 3.5: Information on the usage of fan and /or electric heater during the monitoring periods.

Building	Office	Fan	Electric heater
Heavyweight	NH1	.	x
	NH2	x	x
	NH3	.	x
	NH4	x	x
	NH5	.	Y
	NH6	x	x
	SH1	x	.
	SH2	x	Y (once used over a weekend)
	EH1	x	.
Lightweight	WL1	Y	x
	WL2	.	Y
	WL3	.	x
	WL4	.	x
	WL5	.	Y
	NL1	Y	.
	SL1	Y	.
	SL2	.	.
	SL3	Y (had also an AC installed after monitoring)	.
	SL4	x	.
	SL5	Y	.
	EL1	x	.
	EL2	x	.

Note: 'x' indicates no fan / electrical heater used during the monitoring period, 'Y' indicates fan / electric heater was used during the monitoring period, and '.' was used if the office was not monitored during winter / summer .

The effect of the portable heaters / fans were taken into consideration during the analysis of the results obtained from the indoor air temperature monitorings and the surveys. For other equipment it is safe to assume that during daytime when the occupants were in their offices they all had approximately the same internal heat gains from the electrical and hence was disregarded in the analysis. The occupant of SL3 installed a portable AC in his office, however the occupant was asked to mention on the questionnaire if the AC was on. Since the installation was just after the mini heat-wave, he did not actually use it during our monitoring.

The multi-occupancy offices in the heavyweight building all have one printer and each student has their own computer. The number of computers in each room was dependent on the maximum number of occupants expected in the room (Table 3.3). The number of computers switched on depended on the number of students present during daytime, with the majority of the computers switched off over the weekend. NH6 had one small fridge (approximately 0.8m x 0.8m x 0.8m) and one student had a desk lamp whereas SH2 had one kettle. However, during weekdays, the number of occupants in NH6 was usually less than the number of occupants in SH2 and therefore the assumption is that the heat gain in NH6 from the fridge is expected to be similar to the heat gain from the higher number of computers working in SH2.

Offices NL1 and SL5 both only had computers and no desk lamps or printers. There were less occupants in SL5 than in NL1, and therefore the heat gains from the computers were expected to be higher in NL1 than in SL5.

For the multi-occupancy offices the number present on the day of the survey was expected to affect the indoor temperatures reached, and this was taken into consideration during the analysis of the results.

SUMMARY

Two buildings at the University of Bath, 4E (lightweight) and 6E (heavyweight), have been chosen as case study buildings, due to their difference in thermal mass. Offices have been selected from both buildings with various orientations, locations and occupancy levels, to provide a representative sample of offices. The following chapter describes the methodology adopted for the field study in order to verify or reject the hypothesis.

Chapter 4

EXPERIMENTAL INVESTIGATION

Real world research (Robson, 1993) is different from the research performed under controlled conditions, such as in laboratories (labs) or chambers. Research executed under real life situations are considered to be complex and uncontrolled and hence chaotic, but unlike lab-based research, they directly represent reality (Robson, 1993). Research under real conditions can be performed using one of three following methods (Bryman, 2008):

1. Quantitative research: Research carried out on numerical data. For example, readings from a temperature sensor. (Also known as objective).
2. Qualitative research: Research carried out on data other than numerical data. For example, data from interviews, observations, questionnaires etc. (Also known as subjective).
3. Mixed-method research: incorporates both quantitative and qualitative research.

Mixed-method techniques were incorporated in this study and a detailed description of these methods can be found in this chapter. The reasons for deciding to use both subjective and objective data collection methods are as follows (Bryman, 2008):

1. Quantitative and qualitative research findings can be substantiated by each other.
2. Mixed-method research overcomes the weaknesses of each separate method by outweighing their respective advantages.
3. The quantitative results can be used to assist in the interpretation of the qualitative results.
4. Investigating both the quantitative and the qualitative aspects can give more insight to answering the proposed research questions.

4.1 Quantitative Data Collection

The indoor environment is not constant, it varies all the time and in space, hence it is important to consider the location of the sensors in three dimensions (ISO 28802, 2007). However, the limited number of instruments available for the study influenced the position of installation of the instruments. Below is a description of how the various positions of the instruments were decided, with details on the type of equipment used and their limitations.

4.1.1 Deriving the Methodology

In order to meet the objectives of the study (Chapter 1), the equipment had to be carefully allocated. Having only one globe thermometer, eight air temperature sensors, six state loggers and two carbon dioxide sensors meant that gridding the offices and installing sensors at various positions (horizontally and vertically) was not feasible as one room would then be examined at a time. The offices are relatively small (when compared to lecture theatres etc.), so stratification of the temperature was not believed to be a major problem. This was confirmed through a pilot study that was performed in order to find the ideal position for the installation of the sensors. Temperature sensors were placed vertically at approximately 0.5m spacings starting from ceiling level and approximately every 1m across a room located in 6E, and the temperature difference was found to be less than 0.5°C. The position of installation for the various instruments is discussed in the relevant sections.

In many previous studies, it was found that the air temperature and the mean radiant temperature are almost the same, and hence it does not matter which one is measured (Humphreys, 1976). It was thus decided to measure the air temperature using a Tinytag and the globe temperature (usually its value lies between mean radiant and air temperature) using a globe thermometer. The difference at any given time between the Tinytag and the globe thermometer (occupied and non-occupied periods) was never exceeding the suggested 2°C (Humphreys, 1976) – the maximum difference was ±0.4°C. Further, the air velocity was less than 0.2m/s. Humphreys (1976) suggested that if the air velocity is less than 0.2m/s the air temperature could be used to represent the temperature of the environment measured. Consequently it was decided to use the air temperature to represent the temperature experienced by the occupants, as there were eight Tinytags but only one globe thermometer.

Further, in order to avoid losing data due to instrumental problems, since they were not automatically sending the data to a computer, results were taken from the equipment on a weekly basis, and the equipment was checked prior to re-installation for battery status, errors etc. Nevertheless, like in any experiment, things can go wrong with the installation or with the equipment, and this study was no exception. One of the two CO_2 sensors stopped working during the monitoring period, and the results were lost. It was subsequently found that the sensor had a problem with the charging process, a problem that did not exist for the previous studies.

4.1.2 Indoor Air Quality Sensor

Humphreys (1976) describes various techniques of measuring ventilation and dictates that recording CO_2 levels is one of the easiest and simplest methods due to the equipment used for the measurements. The indoor air quality (IAQ) sensors used were the TSI Model 7525 (TSI,

2010) (Figure 4.1). Since the instrument can take various types of readings, it has various accuracies for each type of reading it records. Reference to its accuracy is made to only the ones measured (Table 4.1).

Table 4.1: Specifications of various measured environmental factors recorded by the IAQ sensor.

	Accuracy	Resolution
Carbon Dioxide	±3.0% of reading or ±50 ppm (whichever is greater)	1 ppm
Temperature	±0.6˚C	0.1˚C

Note: More information on the specifications of this IQS model can be found on their website www.tsi.com.

Calibration was not done before starting the experiments (as they were new and recently calibrated). However, the two CO_2 sensors were tested against each other for discrepancies in their readings by placing them in the same environment away from the occupants. Results indicated that they were agreeing within 45 ppm on average[1].

Figure 4.1: IAQ sensor used for the study.

Note: The red oval indicates the position of the sensor.

CO_2 exhaled by humans contains between 35,000 to 60,000 ppm, which is more than 100 times higher than the concentration in the outdoor air (Prill, 2000), hence it is important to install the IAQ sensor at a sufficient distance from the occupants in order for the exhaled air to mix properly with the indoor air.

In order to find the ideal position of the CO_2 sensor it was decided that it should be suspended at various levels in the pilot study. It was observed that it had to be approximately 1.0m radius away from the occupant in order for the CO_2 levels to be accurately measured, as otherwise, exhaled air did not properly mix with the air in the room, and the readings were not representative of the actual CO_2 levels (distance between occupant and sensor, $d < 1$m, average CO_2 = 1580 ppm, $d \geq 1$m average CO_2 = 640 ppm). It was decided to have the sensor at the same height as the temperature instrument (0.5m from ceiling) for two main reasons :

1. Out of reach of occupants in the office,
2. Sufficiently high to enable proper mixture of indoor and exhaled air.

In some cases the CO_2 sensors were stuck to the ceiling, in other cases clipped to I-beams etc., depending on the construction of the room. Hot and cold spots were avoided as that would make the readings unreliable (Chapter 2).

Since there were only two CO_2 sensors available, there was no space for constant monitoring of the external CO_2 levels. However, having measured the external CO_2 levels over a day in May it was on average 380 ppm (±50ppm) which is within the experimental error with the actual CO_2 levels measured by the National Oceanic and Atmospheric Administration (NOAA) for the

[1] ppm – parts per million

month of May (390 ppm) (NOAA, 2009). This comparison meant that external CO_2 levels could be obtained any time from NOAA, where their data is collected from Mauna Loa, Hawaii, which avoids any local effects and represents the global average.

4.1.3 Air Temperature Sensor

There were four different models of sensors (TGP-4500, TGU-4500, TV-4500, TH-2500) (Tinytags, 2010) used for measuring air temperature and relative humidity in this study (Figure 4.2). Relevant information with respect to their specifications and area of usage can be found in Table 4.2.

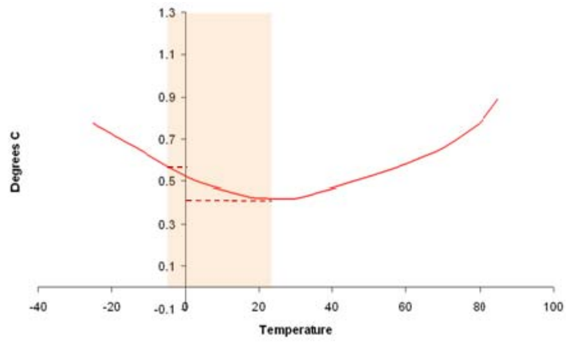
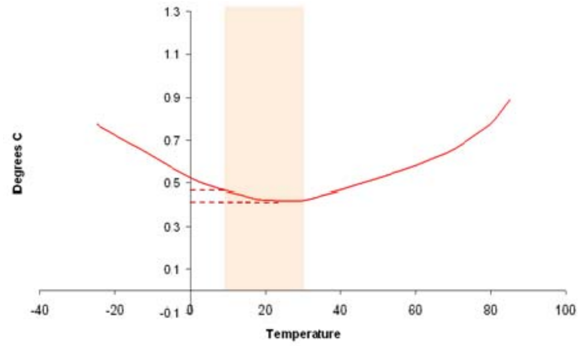
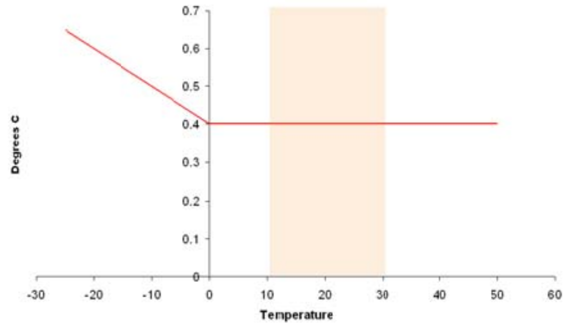
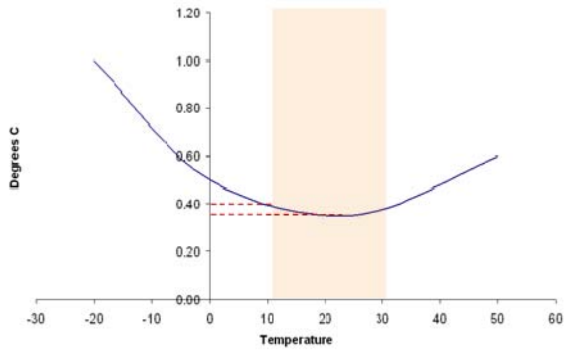
Figure 4.2: Air temperature and humidity sensors used for the study.

*Note: The first sensor on the left is **TH-2500,** the middle top sensor used is **TGU-4500,** the top right sensor is **TGP-4500,** and the bottom sensor is **TV-4500. T**he red circles indicate the position of the sensor for each model.*

The evaluation of temperatures in NV buildings over various seasons is essential in order to assess the thermal comfort inside the buildings (Wouters, 2002). Wouters (2002) advises using small stand-alone sensors, which are easy to install, relatively cheap and have a good accuracy for the readings (1°C or better). It is further explained that the temperature is not uniform in the room, and hence if the sensor is placed near a wall it will record different temperatures compared to the air temperature of the room, with the air temperature usually being higher than the wall during day-time and vice versa during night-time. McIntyre (1980) suggested that if the temperature is uniform within a room a single sensor is sufficient for individuals spaced up to 5-10m apart.

ISO 28802 (2007) suggests that the sensor should be positioned near the working space of the occupants in order to be truly representative of the thermal environment experienced by the occupants. However, all occupants were seated near the windows and so it was decided that it would be more appropriate to not leave them on the desks of the occupants to avoid cold spots. The sensors were suspended from the ceilings away from direct sunlight, as they are hot spots, and away from draughts, as they are cold spots, in order to ensure good results. Further, there were not enough sensors to be placed on each desk of the occupants in the multi-occupancy offices so this way of installing the sensors represents the average air temperature experienced by all the occupants in the office.

Table 4.2: Specifications of temperature and humidity sensors.

Model	Area of Usage	Accuracy for Temperature	Accuracy for Humidity
TGP-4500	External	 (Resolution <0.01°C)	±3.0% at 25°C (Resolution <0.3% RH)
TGU-4500	Internal	 (Resolution <0.01°C)	±3.0% at 25°C (Resolution <0.3% RH)
TV-4500	Internal	 (Resolution <0.02°C)	±3.0% at 25°C (Resolution <0.3% RH)
TH-2500	Internal	 (Resolution < 0.05°C)	±3.0% at 25°C (Resolution <0.3% RH)

Note: The red dashed lines indicate the accuracy region for this case.
Reference: the graphs were modified from the originals www.geminidataloggers.com.

The surface temperature of a human is normally warmer than the temperature of the surrounding air, hence warming up the clothes as well as a layer of air which is in contact with his / her skin (McIntyre, 1980). This air either rises naturally due to buoyancy forces, and hence can be detected at over 1m above the head or be blown away due to a draught (McIntyre, 1980). Consequently, the temperature sensor was not placed directly above the occupant, but at a minimum of 1m radius from the occupant's head, and 0.5m from the ceiling to fit in that range.

Similarly, having only two sensors available for measuring the external conditions of the offices, pilot studies were performed to find their best positions. The lightweight building has a courtyard in the middle of the building, with a deciduous tree in its centre reaching up to the top of the building. The effect of the tree on the external temperature of the offices facing the courtyard and thus creating a different microclimate was tested over summer, as in winter it is not expected to have a major difference between the various offices. It was found that the assumption that the tree was creating a microclimate was correct, as the air temperature recorded by the sensor on the wall of the non-shaded office was 1-3°C higher in the afternoons than that recorded by an identical sensor placed outside an adjacent office shaded by the tree.

Ideally, the external sensors should be covered by a Stevenson screen[2] (Humphreys and Nicol, 1995), in order for the sun not to have an effect on the readings. The department does not have one, therefore it was decided to suspend the sensors in the shaded area (north facade), to avoid hot spots. When suspending the Tinytags from the windows, the wind was swinging them round, and consequently at some points the sensor was facing the facade measuring its radiant heat and not pure air temperatures. It is known that heat is radiated from the facades of the building. As the thickness of the 'zone' is unknown, it was assumed to be around 5 cm (it depends on the properties of the internal and external facade and the insulation etc.). Consequently, the temperature sensor was stuck on the facade facing away from the building, in order to be away from this heat exchange zone, thus ensuring only the actual external air temperature was measured. As the air temperatures recorded were more representative of the external air temperatures once the sensors were fixed in one place, this assumption must be representative of the reality.

As Priolo (2002) has commented, there are differences in the temperature of the air as there are exchanges of air just below and just above the window, and hence installing any sensor near that area would result in false readings. Consequently, the sensor was suspended outside the window to about 40cm from the opening of the window, so that when the window was open the sensor was beyond that zone, and did not measure warmer air temperatures coming from inside the room. Longer distances were not selected, as then sticking it to the facade was either not possible or inhibited by health and safety reasons.

The summer study was more extensive, due to being a more critical period, as the lightweight building is more prone to overheating. The length of each set of monitoring lasted for ten working days, to ensure that any overheating patterns were not an extreme event. One of the weeks the monitoring took place had a mini 'heat-wave'. A similar study lasted only three days, (Dahlan *et al.*, 2008), and hence ten days was thought to be good as any longer periods would

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[2] Stevenson screen – a white louvered box where instruments such as the temperature sensors are placed to protect them from direct and reflected sunlight, and from precipitation. Reference: ECGL (2007) Stevenson Screen. In: *Environment Canada's Green Lane (ECGL).*

mean subjects get bored or start to repeat their votes. Some of the occupants were not willing to participate for that long and hence the study was limited to five working days in their office.

4.1.4 State Logger

Hobo state data loggers (MicroDAQ, 2010) were used for this study to monitor the operation of the windows and doors. They have a time resolution of half a second, and a time accuracy of one minute. The state logger is composed of a sensor containing an internal magnet and an external magnet (Figure 4.3), which are attached to the two sides of the openable object (for example, door and door frame). The gap between the two magnets must be less than or equal to 0.6cm for the HOBO state logger to detect the openable object as closed, and more than 1.9cm to detect it as open; the state was shown with a green / red flashing light.

The state loggers were installed on the doors and on the windows of the offices. The type of windows were different for the two different type of buildings (Chapter 3), but it did not change the installation of the equipment.

Since there were only six HOBO state loggers, they were installed on the windows that were most often used (according to the occupants), in the autumn to spring studies. However, for the summer study, the questionnaires were modified for the occupants to mention if they had their windows open or closed as there were not enough loggers to install in all offices. This could have made the occupants aware of their operation of the windows and perhaps they could have started to operate them differently.

Figure 4.3: The HOBO state logger.

The pilot study, however, pointed out a possible problem that was to be encountered with this methodology for the multi-occupancy offices. For example, when the subjects of a multi-occupancy office were asked to mark on the questionnaire the number of windows open at the time of replying to the questionnaire, some sitting away from the windows marked less number of open windows than there were at that instance. In order to minimize that problem, near the timings which the occupants were filling the questionnaires in, inspections were carried out to verify which windows were open.

Another problem with the installation of the sensor was that it does not give any indication of how much the door or window is open by. The amount of window opening could be found by installing sensors at different heights on the window frame, but that requires lots of sensors and hence it was not a feasible option. Consequently, the assumption that no matter how much the window or the door was open there was always a constant exchange, was incorporated. This does not however represent the opening of the door, which the sensor could record when in reality it was just touching the door frame, but the error caused is not of a significant level for the purpose of this study.

4.2 Qualitative Data Collection

Two different sets of occupants were used in this study, and hence there were some differences in the methods used to collect the subjective data.

4.2.1 The Subjects

The participants of the study consisted of two groups: (i) research students and (ii) academics. Both the occupants of the single-occupancy offices (academics) and the multi-occupancy offices (research students) are likely to vary in the timing they spend in their offices depending on their area of specialization. Some research students, for example, work in labs which are located in the basement and are constantly cooler than their offices. Therefore, to ensure that the subjects' comfort votes are not biased, they were asked to be in their office for at least 15 minutes before they answer any of the questionnaires (Goto *et al.*, 2007, Wagner *et al.*, 2007). These 15 minutes are necessary in order to ensure thermal stability between the occupants' previous thermal environment and their current environment, which is measured. It is still acknowledged that people who experience cooler environments throughout the day might be acclimatized to their office environment, and hence perceive the temperature differently than when they are in their office for the whole day.

4.2.2 Questionnaire Purpose

The aim of the questionnaire in this study is to investigate the range of temperatures the occupants are most comfortable with and what they do in order to minimise their discomfort at various times of the year. Occupants would be asked to fill in the questionnaire more than once a year, and hence it was kept short to be convenient for the occupants. It was decided to go for two different sets of questionnaires: (i) longitudinal and (ii) transverse.

Longitudinal questionnaires are given to the subjects on a regular basis over a short period of time, for example on a daily basis for a month, or three times a day for a week, and thus a large amount of data is collected over a short period of time (Nicol, 2008). The sample size of occupants is much smaller for the longitudinal questionnaires when compared to the transverse questionnaires, as it is a less focused study (Gillham, 2007).

Over autumn and winter a transverse questionnaire was given to all occupants whose offices were monitored. This questionnaire was three pages long and contained more questions to find out more details about their environment and help us understand the factors behind the results obtained from the longitudinal surveys. The transverse questionnaire is usually completed once during the monitoring period, and is more detailed than a longitudinal one (Nicol, 2008).

4.2.3 Questionnaire Design

Some important points that were taken into account for the questionnaire designs are (Gillham, 2007):

1. The aims of the study were clearly stated to the subjects, as was the direct effect of the study on them.

2. Assurance of anonymity, so that they can reply to the questions without fear of saying something deemed to be bad.
3. The questions were prioritized with the easiest first, as that would maximize the response rate.
4. Not to have leading questions, i.e. influencing the response of the subjects.
5. Keep the questions simple, assuming the subjects do not have an environmental education, although some of them do have a solid environmental background.
6. Freedom to express opinion. There was a comments line at the end of each question. Some subjects used them and gave reasoning behind their selection of values.
7. Avoided the yes or no answers as they tend to give little information.
8. Kept the questionnaire short.

Following is a description of the questionnaires making specific reference to the two different questionnaire designs, and how the pilot study influenced their design.

4.2.3.1 Longitudinal Questionnaire

The longitudinal questionnaire (Appendix 1) was one page long, and consisted of questions related directly to the window and door opening, and the thermal comfort of the occupant. Other information asked for included the clothes worn at the time of the study, and information on timing. This questionnaire had to be as short as possible as some of the occupants had to fill it in twice a day, once in the late morning (9.00 – 11.00) and once in the late afternoon (15.00 – 17.00), or later three times a day during the summer period monitoring (9.00 – 11.00, 12.00 – 14.00, 15.00 – 17.00).

4.2.3.2 Transverse Questionnaire

The transverse questionnaire (Appendix 2) was divided into three sections. Section 1 was a fingerprinting for the offices (Levermore and Leventis, 1997). (More information on fingerprinting can be found in Appendix 3).

Section 2 consisted of various factors that could influence the comfort of the subjects in their office, related to the windows and other more general questions on how the subjects feel about their space, in order to appreciate the reasons why the occupants feel the way they do in their space. The general factors were, for example, how noisy they feel their environment is, and where the noise comes from. If the noise levels receive a low value (i.e. occupants are not content with it), and the noise was mostly coming from outside, this could be an explanation to why occupants did not open their windows. Therefore, indirect questions relating to thermal comfort were incorporated in this section as there could be some influential factors to the thermal comfort sensation, or the air quality of the offices.

Section 2 was based on a seven-point scale, despite McIntyre's (1980) and Gillham's (2007) suggestion to avoid seven-point scales as people tend to ignore most of the answers, or get confused in terms of which answer is more suitable to them. This section incorporated questions on thermal comfort which were based on the seven-point ASHRAE scale (1 = hot, 2 = warm, 3 = slightly warm, 4 = neutral, 5 = slightly cool, 6 = cool, 7 = cold). It was therefore decided, for uniformity, ease of understanding and simplicity, to use that scale throughout this section. Presentation of questionnaires plays a critical role in the subjects' overall perception of the questionnaire and hence in the way they respond.

McIntyre (1980) had suggested that in thermal comfort studies information on the activities and clothing is essential. In this case, activity is almost the same for all cases as when they are in their office people will be doing desk-based office work. Consequently, section 3 consisted of a table where occupants ticked the clothing they wore at the time of filling in the questionnaire. Thereafter the clothing insulation of the occupants was calculated. Section 3 also incorporated demographic information.

After the first questionnaire design, a pre-pilot study was conducted, where people in the same field of research were asked to read the questions and tell me if it was clear to them what was being asked in each question and to see if they agreed on the ordering of the questions etc. This helped to rephrase certain questions for ease of interpretation by the subjects.

Following the pre-pilot study there was a pilot study where people from outside the faculty, and hence not in the same field of research, were asked to fill in the questionnaire, and explain how they derived their responses. After this study certain questions had to be further rephrased or be made more specific, such as, for example, whether the conditions were felt at that specific moment of the question-answering session or in general. Further, in the questions it was required to emphasise the word YOU, as many questions could be misinterpreted. For example, a question phrased 'how warm is your office now' in a multi-occupancy office could be misleading, as the subject could interpret it as how warm people in general feel in the office, instead of how warm they personally feel in it. The question therefore had to be rephrased to 'how warm do YOU feel in your office now'. Another improvement was to write a note on the questionnaire to the subjects asking them not to discuss answers amongst themselves.

It is necessary to think of the group being targeted prior to writing the questionnaire. This study involves people directly engaged in environmental design, and when talking about temperature drifts for example, they could easily understand what was meant. However, it also involved people who are in structural design, with minimal environmental knowledge. Therefore, in the pilot study people not related to environmental design were asking the meaning of the questions and hence some had to be rephrased, such as asking 'how often the temperature goes up and down in your office throughout the day' instead of 'temperature drift'. The study involves highly educated people which mitigated the necessity for lots of explanations as would be required if the target group was of a different educational background.

4.2.4 Questionnaire Completion

Occupants were filling in questionnaires when their office was monitored. The occupants of the single-occupancy rooms were asked to fill in a longitudinal questionnaire twice a day during autumn, winter and spring, and three times a day during the summer period when academics are likely to be more available. The monitoring period could range from a couple of hours to one day and up to ten days. The reason for such variation was due to the occupants being available for different periods of time. For example, there was no female data for the 4E west-facing offices, so it was preferred to do the monitoring over a couple of hours as that was the only available timing the occupant was willing to assist.

The main reason behind completing the questionnaires twice / three times a day was to see if there were any differences in the comfort of the occupants' throughout the day. The temperature of the human body changes (by 0.7°C) as the day proceeds with the maximum occurring late in the afternoon and the minimum occurring early in the morning (Mount, 1979), hence it is expected that the conditions an individual will prefer will be different as the day progresses (ASHRAE, 2005). Further, since only two offices could be monitored at a time, having two questionnaires a day meant more responses, giving more validity to the results.

The subjects for the multi-occupancy offices were asked to fill the questionnaires initially once a day, as enough data could be gathered from each office with just one questionnaire. However, for the more intensive study, it was decided to give each questionnaire three times a day if the occupants were willing to assist. Occupants were asked to complete the transverse questionnaire whenever they had free time throughout the monitoring period. However, as expected in all field surveys not all occupants were willing to participate, even though they had initially agreed.

4.2.5 Questionnaire Distribution and Collection

In order to maximize the response rate of the questionnaires, there has to be an in-depth understanding of what type of people are being surveyed. Questionnaires can be done online, or sent in an envelope or even be given in person etc. (Walonick, 2004). Each method of allocation has its advantages and disadvantages, and no matter how they are given they have to stand out in order to ensure that the subjects will not just disregard them.

In this case, placing the questionnaires in the pigeonhole of the occupants' means they could easily have ignored them. Sending the questionnaires in an email format means that the occupants would have to print them, and so even if the emails did not end up unopened or completely forgotten in an inbox, they might never be printed, and hence never completed.

Nowadays, online surveys do not have the problem of identity, or of stopping them and continuing them later, as there are different software packages available online that enable that, but only after purchasing the full version, which was not viable in this case. Furthermore, a vital disadvantage of this method is that the respondents filling them in online might not open the emails with the links, as was the case with a few questionnaires distributed via email this year from various other departments to the Department of ACE. Nevertheless, even if the respondents replied the first time, there would be a high risk of not filling them in for the consecutive studies, as some respondents could say that they already completed one online questionnaire for this study.

Under the circumstances of this study, and as the sample was relatively small, the most efficient way would be to give the questionnaires in person. An introduction was given to the subjects individually in their office, and included key things such as the purpose of the study, instructions on how to fill in the questionnaires and how long completion of the questionnaire would take. Thereafter, according to the most suited method for the occupants a reminder was given either by email or in person.

The most productive collection method would be to collect the questionnaires in person from their office where answers could be discussed through an informal personal interview. Posting the replies, or getting them to place them in a collection box, meant that some occupants could actually not complete the questionnaires as it would be harder to notice who did not respond. In the pilot study there was a 100% response rate and hence it was decided to adopt the same methodology for all the surveys i.e. hand-out the questionnaire in person to the participants and collect it on the same day for the multi-occupancy offices, and for the single-occupancy offices to collect them at the end of the study but sending frequently reminder emails. As more occupants were asked to fill in the questionnaires, although the response rate decreased, it was still high with overall 88% response for the transverse questionnaires and 87% for the longitudinal ones for the single-occupancy offices, and for the multi-occupancy office the response rate was 92% for the transverse questionnaires and 79% for the longitudinal ones.

4.2.6 Limitations

The thermal comfort vote of the occupants can be interpreted differently amongst the occupants. However, the larger the number of the occupants participating in filling in the questionnaires, the more reliable the vote will be (Hens, 2009).

The longitudinal questionnaire was meant to last for two working weeks. However, some of the occupants were not content to participate for that length of time, and hence the period the study was run for was modified accordingly. Since the number of occupants facing in each direction of the building was minimal, it was decided to adjust the study accordingly in order to have as much data as possible.

Ideally, all the questionnaires should be filled in at the same time, to correlate the responses and the environmental conditions at the same time. It was acknowledged that academics have varying schedules and consequently response rates were higher by giving flexibility in the filling in time of the questionnaires, as it was expected that the temperature variance would not be much within the two hour gap they were given. The response rate was 96%, as only a few occupants in the multi-occupancy offices were not completing questionnaires.

4.3 Monitoring Periods

The monitoring took place over the four seasons, whilst incorporating any sudden changes, such as heavy snow, or a sudden heat-wave, to see the effect on the perceptions of the occupants to the sudden and gradual changes. Furthermore, monitoring over the different seasons gave an indication of how the buildings perform under various external conditions (Chapter 6).

The selection of the offices for each monitoring period was firstly based on the availability and willingness of the subjects to participate in the study. Overall, subjects were chosen in a way such that at any monitoring period there were readings and questionnaires from the two buildings of different thermal mass (lightweight and heavyweight), or were from the same building but facing opposite orientations. There were two single-occupancy offices, located next to each other being monitored at any one time in each building, to ensure that the readings were not special cases. In some instances there was one female and one male occupant to investigate their variation in the subjective analysis. Since the multi-occupancy offices were not located next to each other in each building, bias replies to questionnaires were avoided by having more than two occupants replying at the same time for the same indoor environmental conditions.

Questionnaires were filed in twice a day, once in the late morning (9.00 – 11.00) and once in the late afternoon (15.00 – 17.00), during the semester monitoring periods, or three times a day during the summer monitoring (9.00 – 11.00, 12.00 – 14.00, 15.00 – 17.00). The aim of this was to see how the perceptions of the occupants changed throughout the day. Further, summer is considered as the most vulnerable period for overheating of the buildings, and hence the occupants were asked more often to fill in the questionnaires. The timings to fill in the questionnaires were decided in accordance with the operation timings of the Faculty of Engineering and Design which is from 9.00 to 17.00. Giving a time range rather than a specific time provided flexibility to the occupants filling them in, and hence maximizing the response rate.

SUMMARY

The methodology adopted for this study has been explained in this chapter. There was both an objective and a subjective part to the study. Measurements taken in the various offices included air temperature, relative humidity, carbon dioxide and window and door operation. The position of placing the sensors, and the description of how the questionnaires were completed were all discussed in this section. The first limitation of the study regarded the equipment used and the second the questionnaires. The following chapter looks at the results obtained from the study.

Chapter 5

RESULTS AND DATA ANALYSIS

The analyses of the subjective and objective data collected from the field surveys are presented in this chapter. It is comprised of two main sections: Section 5.1 concentrates on the monitored data collected (air temperature, relative humidity, window states, door states and CO_2). Section 5.2 focuses on the subjective data collected from the questionnaires and informal interviews (comfort votes and clothing insulation values).

5.1 OBJECTIVE DATA

The analysis of the objective data collected commences by looking at the external conditions during the monitoring periods. The results collected from the various offices are then presented, starting from the summer and spring monitoring where the main study was undertaken, followed by the winter and autumn monitoring. The findings are categorized into sections: (i) thermal mass, (ii) orientation and (iii) occupancy levels.

5.1.1 EXTERNAL CONDITIONS

Average external air temperatures from the monitoring periods are summarized in Table 5.1 and are compared with (i) the average monthly temperatures recorded for south-west England over the period of 1971-2000 and (ii) the averages of the months of 2009, both monitored at Yeovilton station. Yeovilton station is the nearest to Bath.

Table 5.1: External temperatures from on-site monitoring and from the Met Office during the monitoring period of offices.

Date	**Outdoor air temperature (24hr) (˚C) (% RH)**[i]			**Mean temperatures from the Met Office**[ii] **(˚C)**			**Historic mean temperatures from the Met Office**[iii] **(˚C)**			**General Information**[iv]
	Av	**Max**	**Min**	**Av**	**Max**	**Min**	**Av**	**Max**	**Min**	
10/10/08 – 11/11/08	9.25 (85.4)	19.7 (68.6)	-1.14 (94.9)	9.40	22.2	5.70	9.08	12.9	5.25	**Coldest October since 2003**, with November having temperatures similar to the expected average temperatures.
12/11/08 – 01/12/08	6.87 (63.2)	13.6 (86.7)	-0.80 (93.8)	7.40	10.5	4.20	7.35	11.1	3.60	
04/12/08 – 08/12/08	4.58 (77.2)	7.72 (92.6)	1.55 (100)		*7.40*	*0.20*	5.70	9.00	2.40	Temperatures were about **1˚C lower than the historic mean** temperatures.
28/01/09 – 09/02/09	1.72 (81.6)	8.87 (99.8)	-4.24 (100)	*3.85*	*7.20*	*0.55*	4.78	8.20	1.35	The **coldest January since 1997**, and in February (3rd, 4th & 5th) there was **heavy snowfall**, especially in south-west England.
09/02/09 – 19/02/09	5.40 (85.9)	11.9 (78.2)	-1.58 (100)	4.50	11.0	-3.60	4.80	8.30	1.30	
26/03/09 – 02/04/09	8.45 (71.9)	16.9 (44.7)	2.49 (87.8)	*8.35*	*13.2*	*3.50*	6.65	10.6	2.70	**April** was **warmer** by about **1.3˚C** for south-west England **than the 1971-2000** average temperatures, and **May** was **warmer** by about **1.5˚C**.
27/04/09 – 06/05/09	11.9 (79.3)	21.7 (47.6)	3.29 (100)	*11.1*	*15.9*	*6.20*	9.98	14.7	5.25	
06/05/09 – 13/05/09	11.9 (80.0)	24.3 (37.2)	4.95 (92.3)	11.6	18.6	1.40	11.7	16.5	6.80	
22/06/09 – 03/07/09	21.0 (70.0)	37.2 (31.0)	10.2 (89.2)	*16.0*	*20.5*	*11.5*	14.5	19.3	9.7	In **June temperatures** were **1.5˚C higher than the average 1971-2000**. The temperatures were very warm until the beginning of **July**, followed by normal temperatures. The south-west received **three times the normal amount of rainfall**.
06/07/09 – 15/07/09	17.3 (76.7)	27.3 (44.6)	10.1 (100)	*16.3*	*20.1*	*12.5*	16.8	21.7	11.9	

Table 5.1 shows that the mean air temperatures recorded by the Met Office from 1971 to 2000 are higher than the temperatures recorded on campus over winter, but lower over summer. The discrepancies between the historic mean temperatures recorded by the Met Office and the ones recorded on site at the university can be attributed to the heavy snowfall of winter 2009

[i] Represents the relative humidity corresponding to the outdoor temperature. For example, the corresponding RH at the time the maximum temperature was recorded, and this is not necessarily the maximum RH recorded.

[ii] Using data provided by the Met Office from the Yeovilton station for 2008-2009, the numbers in normal font represent the maximum, minimum and average temperatures whereas the numbers in italic represent the average of the maximum, the average of the minimum and the average of the average for the monitoring period.

[iii] Using the Yeovilton station monthly average temperatures from the period 1971 – 2000. *www.metoffice.gov.uk/climate/uk/averages/19712000/sites/yeovilton.html*

[iv] From the comments made by the Met Office, and are referring to south-west England where Bath is located. *www.metoffice.gov.uk/climate/uk/2009/*

causing the lowest temperatures since 1997, and the mini heat-wave towards the end of June lasting approximately one week. Any other discrepancies could be due to the microclimate of the area (vegetation, topography, buildings etc.) (Leaman and Bordass, 1999a) and the fact that the University of Bath is at higher altitude than Yeovilton station, hence the temperatures are expected to be lower. The record amounts of rainfall and the mini heat-wave are believed to be some of the effects of climate change.

For the analysis of the results, the outdoor air temperature measured on campus will be used as it is more representative of the conditions surrounding the buildings than the temperatures recorded by the Met Office (recorded in a rural area).

5.1.2 Summer and Spring Monitoring

The summer monitoring was undertaken in two phases; phase 1: 22/06/09 – 03/07/09 (capturing a mini heat-wave) and phase 2: 06/07/09 – 15/07/09. The single-occupancy office air temperatures for phase 1 monitoring are summarized in Table 5.2, and for phase 2 in Table 5.3. The results for the multi-occupancy offices are presented in Table 5.4. The spring monitoring was undertaken on various dates between March and May (Table 5.6).

5.1.2.1 Building's Thermal Mass

The average indoor air temperatures reached in all lightweight offices during the first phase of the monitoring (Table 5.2), were higher than the suggested temperatures of the Carbon Trust (2007) (19 – 24°C) for the 24 hour day (including the working hours of 9am – 6pm, indicating the importance of having high thermal mass buildings.

Table 5.2: Temperatures for single-occupancy offices for the period 22/06/09 – 03/07/09.

Single-occupancy 22/06/09 – 03/07/09	Indoor air temperature during working period (9am-6pm) (˚C)			Indoor air temperature (24hr) (˚C) (% RH)			Corresponding outdoor air to $T_{in\ (9am\ -6pm)}$ (˚C)			Correlation of indoor air temperature and outdoor air temperature
Office	Av	Max[i]	Min[i]	Av	Max	Min	Av	$T_{time\ max}$[i]	$T_{time\ min}$[i]	
EH1	24.2	27.2	21.8	23.7 (56.5)	27.2 (58.7)	21.5 (47.0)	22.4	30.1	14.3	Strong (r = 0.710, $p < 0.001$) ($r^2 = 0.504$, $p < 0.001$)
NH2	23.2	27.9	18.0	23.0	27.9	17.9	22.4	28.9	14.1	Moderate (r = 0.617, $p < 0.001$) ($r^2 =0.381$, $p < 0.001$)
EL1	28.7	37.9	19.7	26.6 (47.3)	41.3 (29.2)	18.7 (47.0)	22.4	36.2	14.3	Strong (r = 0.874, $p < 0.001$) ($r^2 = 0.764$, $p < 0.001$)
SL1	26.7	35.4	20.5	25.6 (50.3)	35.4 (40.4)	20.1 (46.1)	22.4	30.7	22.1	Strong (r = 0.713, $p < 0.001$) ($r^2 = 0.508$, $p < 0.001$)
WL1	24.5	32.1	17.9	23.8	32.1	17.4	22.4	32.4	14.8	Moderate (r = 0.669, $p < 0.001$) ($r^2 = 0.448$, $p < 0.001$)

The maximum indoor air temperatures reached in the lightweight offices (on average 35°C) do not comply with any standard, including HSE's (1992) suggestion that indoor air temperatures for sedentary workers should be below 30°C. Contrarily, average indoor air temperatures (~24°C) in heavyweight offices, for that same week, were within the suggested summer air temperature ranges of the Carbon Trust (2007). Maximum air temperatures were within HSE's (1992) suggested maximum. The difference between the average indoor air temperatures of the lightweight and heavyweight offices is significant ($t = -50.2$, $p < 0.001$).

The two east-facing offices located in the two buildings of different thermal mass (EL1 and EH1) exhibit the same 24 hour cycle but with a different pattern for their indoor air temperatures ($r = 0.827$, $p < 0.001$) (Figure 5.1). The lack of thermal mass for office EL1, however, leads to higher indoor air temperatures (Figure 5.2), and allows for greater fluctuations (Figure 5.1) in the indoor air temperatures when compared to EH1 (significant difference: $t = 50.4$, $p < 0.001$).

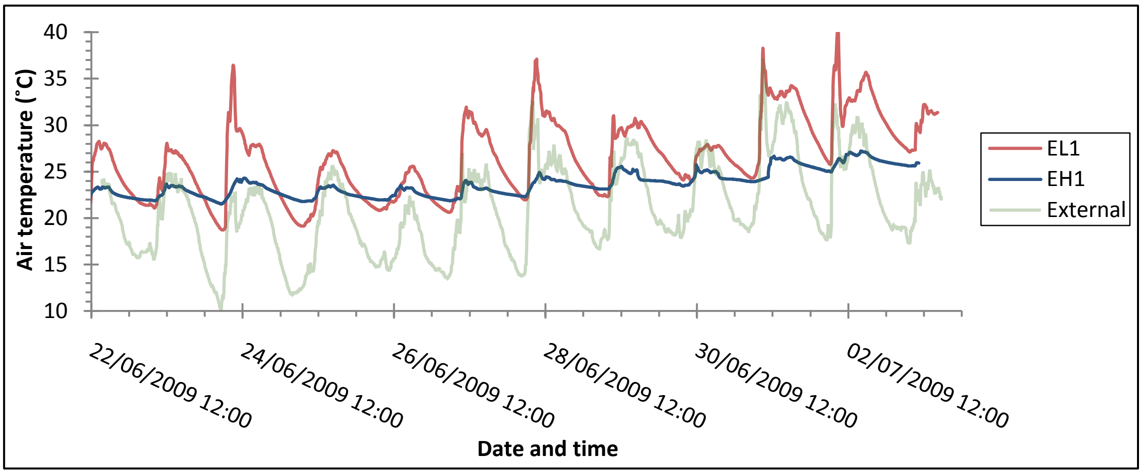

Figure 5.1: Diurnal temperatures for the east-facing single-occupancy offices of different thermal mass.

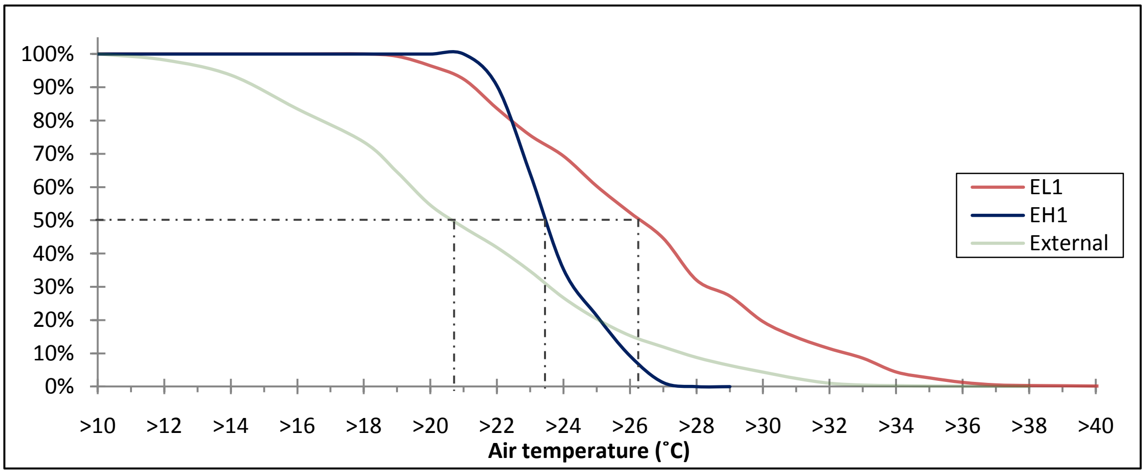

Figure 5.2: Indoor air temperatures for east-facing single-occupancy offices of different thermal mass.

The average indoor air temperature for EL1 is higher than for EH1 by 3˚C. The maximum indoor air temperatures reached by EL1 was around 40˚C (T_{out} = 31˚C), whereas for the corresponding heavyweight office it was 27˚C (T_{out} = 30˚C) (Figure 5.1). Despite the very big difference in the peak indoor air temperatures of the two offices (more than 10˚C), the peak temperature of EH1 is reached within an hour after EL1 reached its peak. Likewise, the minimum temperature of EH1 was also reached within an hour after EL1. The difference in the peak indoor temperatures are due to the thermal mass of the two buildings, the different operation of the spaces (EL1 had only one window open, EH1 had one window and door open – cross ventilation) and due to the different amount of direct solar gains (glazing ratio of EL1 is 50%, EH1 is 25%).

Comparison of indoor air temperatures over the whole monitoring period for two south-facing offices of different thermal mass (SL4 and SH1) (Table 5.3), indicates that the indoor air temperatures are significantly different (t = - 31.4, p < 0.001), likewise with the two east-facing offices (EL1 and EH1). The difference in the average indoor air temperature between EL1 and EH1, and SL4 and SH1, was approximately 4°C (higher in the lightweight offices) despite being monitored at different times (over summer).

Table 5.3: Temperatures for single-occupancy offices for the period 07/07/09 – 14/07/09.

Single-occupancy 07/07/09 – 14/07/09 / Office	Indoor air temperature during working period (9am-6pm) (˚C)			Indoor air temperature (24hr) (˚C)			Corresponding outdoor air temperature for $T_{in\ (9am\ -6pm)}$ (˚C)			Correlation of indoor air temperature and outdoor air temperature
	Av	Max[i]	Min[i]	Av	Max	Min	Av	$T_{time\ max}$[i]	$T_{time\ min}$[i]	
NH4	22.3	25.1	20.1	21.7 (52.2)	25.1 (41.8)	19.8 (47.3)	22.4	20.5	20.3	Moderate ($r = 0.414$, $p < 0.001$) ($r^2 = 0.171$, $p < 0.001$)
SH1	20.5	23.1	18.5	20.2 (53.6)	23.1 (53.1)	18.5 (63.4)	22.4	18.3	20.7	Weak ($r = 0.208$, $p < 0.001$) ($r^2 = 0.043$, $p < 0.001$)
SL2	24.5	29.3	19.6	22.5 (50.4)	29.3 (36.0)	19.2 (56.1)	17.3	21.3	16.7	Moderate ($r = 0.554$, $p < 0.001$) ($r^2 = 0.306$, $p < 0.001$)
SL3	23.1	26.4	18.7	21.6 (50.9)	26.4 (43.2)	18.6 (57.3)	17.3	20.3	16.7	Strong ($r = 0.757$, $p < 0.001$) ($r^2 = 0.574$, $p < 0.001$)
SL4	23.9	28.9	18.6	21.7 (52.1)	28.9 (40.6)	18.1 (70.1)	17.3	21.0	16.7	Moderate ($r = 0.638$, $p < 0.001$) ($r^2 = 0.408$, $p < 0.001$)

The minimum indoor air temperatures for these two south-facing offices are relatively similar (within 1˚C), however, the maximum air temperatures are noticeably different (6˚C) (Figure 5.3).

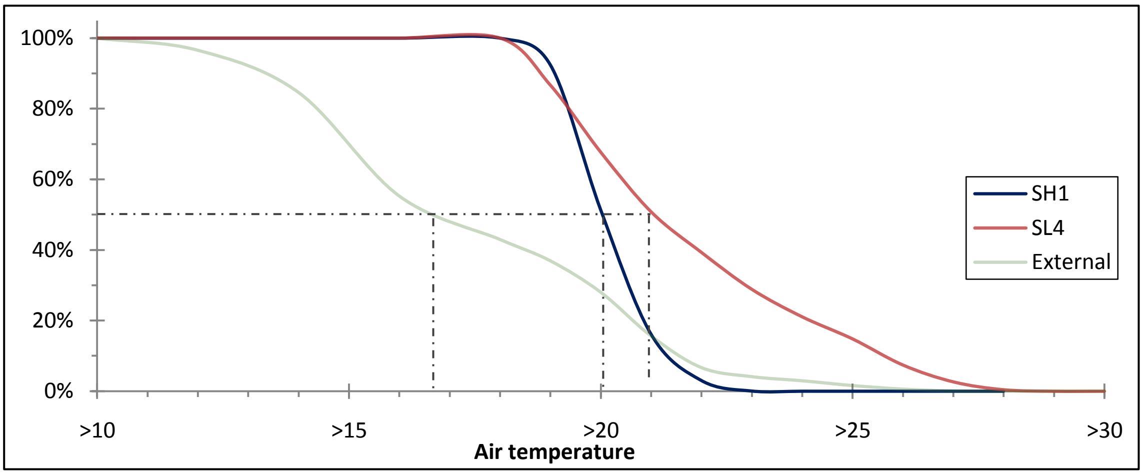

Figure 5.3: Cumulative graph comparing south-facing offices of different thermal mass.

Extreme indoor air temperatures (peak and trough) are reached later (on average two hours later) in SH1 than in SL4 (Figure 5.4) (which is an hour later than for the east-facing offices). Similarly to the east-facing offices, the south-facing lightweight office has overheating periods[v] (temperatures exceed 28˚C), whereas at the same time the heavyweight one is around 19˚C.

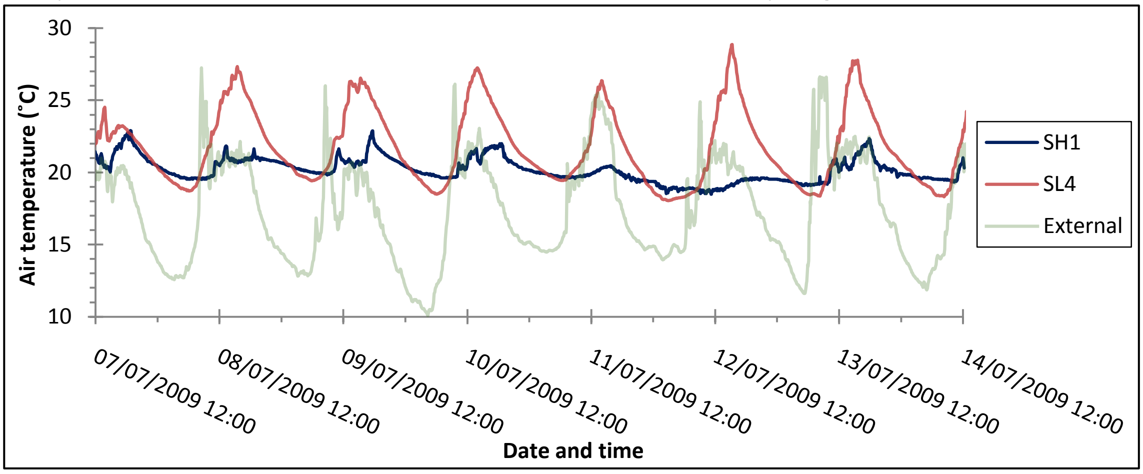

Figure 5.4: Diurnal temperatures of south-facing offices of different thermal mass.

Multi-occupancy offices follow the same indoor air temperature pattern as single-occupancy offices. As expected, the peak indoor air temperature for the lightweight south-facing office is reached before (within an hour) the heavyweight office reaches its peak (Figure 5.5) and within one to two hours for the north-facing offices (Figure 5.6). This is an indication of the effectiveness of the higher thermal mass of SH2. The maximum temperature is in the form of a peak for the lightweight offices, whereas there is a smoother rise for the heavyweight offices and the peak is almost constant for a few hours once the maximum temperature is reached.

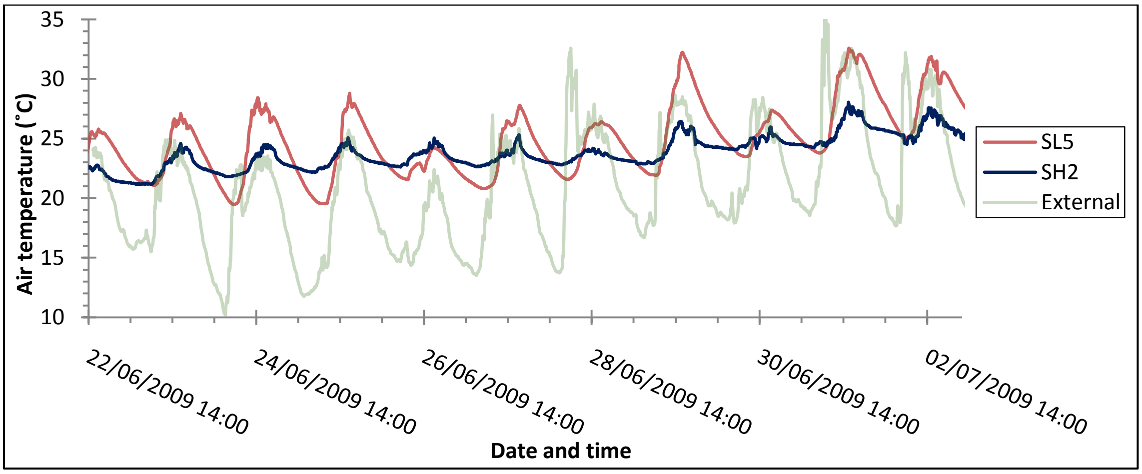

Figure 5.5: Summer temperatures for north-facing multi-occupancy offices of different thermal mass.

[v] The British Council of Offices defines overheating as air temperatures above 27˚C in the offices, for over two consecutive hours. Ward, I. (2004) *Energy and environmental issues for the practising architect: a guide to help at the initial design stage,* London, Thomas Telford Publishing.

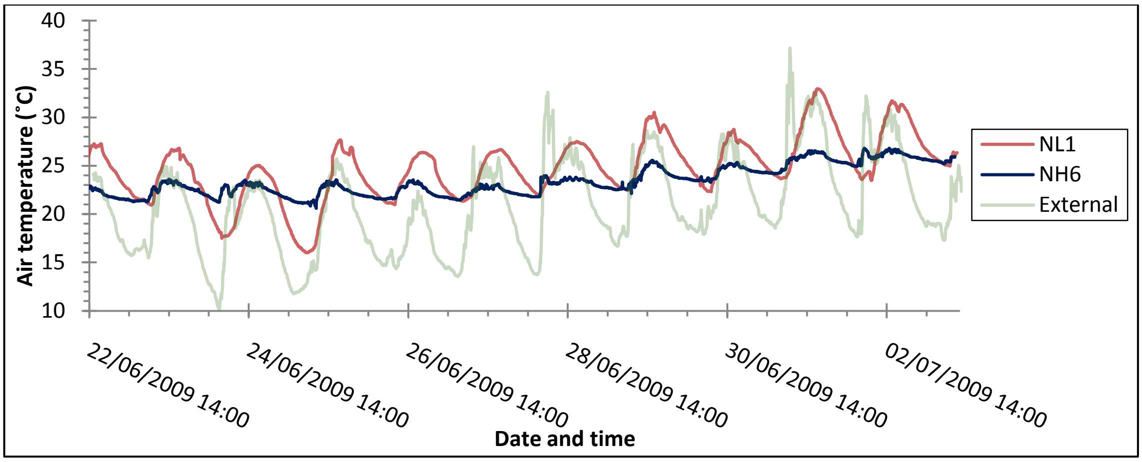

Figure 5.6: Summer temperatures for north-facing multi-occupancy offices of different thermal mass.

Likewise to the single-occupancy offices of the same orientation but different thermal mass analyzed previously, there is a notable difference in the air temperatures of the two south-facing multi-occupancy offices (t = 32.2, *p* = 0.001) and the two north-facing offices (t = 31.5, *p* = 0.001). Even though SH2 had a higher percentage of glazed area (40% of south-facing external wall is glazed, and 10% of the west-facing wall), it still had lower indoor air temperatures than SL5 (50% of south-facing external wall is glazed).

During the heat-wave period some occupants chose adaptive opportunities in the lightweight offices such as using their own personal fan in their office (WL1, SL1, NL1, SL5), and in one extreme case, one of the occupants of the south-facing office installed an AC unit. (The implications of installing an AC unit in an office will be discussed in Chapter 6.) None of the occupants in the heavyweight offices used assisted ventilation. In a few of cases the occupants in the lightweight offices left by 1pm, whereas others (occupants in the lightweight multi-occupancy offices) did not come into their office at all after hearing the weather forecasts and experiencing the previous day's high temperatures.

Comparing WL1's summer and spring monitored indoor air temperatures (Figure 5.7), it can be seen that the average temperature of the office is on average 3˚C higher for a given day in June than a given day in May and 6˚C higher than a given day in March.

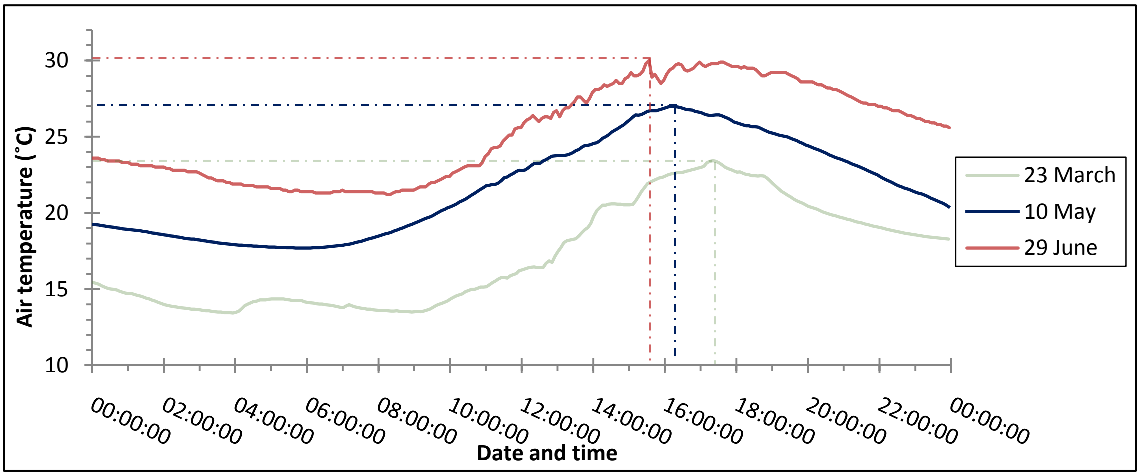

Figure 5.7: Comparing spring and summer indoor air temperatures for office WL1.

The maximum air temperature exceeds the suggested office temperatures of 19 – 24˚C by Carbon Trust (2007), for the days chosen in June and May. Once again, the data suggests that

lightweight offices are highly influenced by the external temperatures, and the problem of temperatures exceeding comfort ranges commences from
late spring.

During the spring monitoring, the difference between night-time indoor and outdoor air temperatures of the north-facing heavyweight offices was 14 – 15°C (Figures 5.3 and 5.4), whereas for the west-facing lightweight offices was on average 11°C for similar spring conditions. Once again, the low heat capacity of 4E caused the indoor temperature to be largely influenced by the external conditions and resulted in 4E loosing heat more quickly. (Details on the offices that this is based on can be found in Section 5.1.2.4).

The conclusion from the summer monitoring period is that the higher the thermal mass of the offices the more comfortable the indoor air temperatures (assuming that the suggested 19 – 24°C is a comfortable range). Even during the second phase of summer monitoring where the external temperatures for 2009 were almost the same as the average 1971 – 2000 temperatures, the maximum indoor air temperatures reached in the lightweight offices exceeded the proposed comfort range by the Carbon Trust (2007).

The variance in the indoor air temperature caused by changes in the outdoor air temperatures for the heavyweight offices is lower (phase 1: 40 – 50%, phase 2: 4% – 17%) than the variance in the indoor air temperature in the lightweight offices (phase 1: 50 – 80%, phase 2: 30 – 60%) (Tables 5.2 and 5.3). Further, the higher the thermal mass of the building the smaller the difference between the maximum and minimum indoor air temperatures (on average 10°C for the lightweight offices and 5°C for the heavyweight offices – Tables 5.2 and 5.3). The correlation between indoor and outdoor air temperatures is strong for all lightweight offices, indicating that indoor air temperatures are largely influenced by the outdoor conditions, which is expected (due to the low heat-capacity and high *U*-value of the external walls of the lightweight building).

5.1.2.2 Office Orientation

The data suggest that for single-occupancy offices located in the heavyweight building, other factors apart from the thermal mass have an impact on the indoor air temperatures reached in the offices. In the lightweight building, office orientation appears to have a significant effect on the indoor air temperatures, with the east-facing offices reaching the highest temperature (T_{av} = 28.7°C) followed by the south-facing offices (T_{av} = 26.7°C) and the west-facing offices (T_{av} = 24.5°C). This is explained below with examples.

Although based on a small sample, the north-facing heavyweight office (NH4) shows a stronger correlation between the indoor and outdoor air temperatures, and unexpectedly generally has higher indoor air temperatures than south-facing office (SH1) (Table 5.3 and Figure 5.8). This could be attributed to the two offices having different size (SH1 is bigger than NH4), or to the varying floor to ceiling height of SH1 (has a sloping roof and so is up to one meter higher than NH4). The position of installation of the sensors was at the same ceiling height and the same distance from the windows and occupants, hence the air temperature of the north-facing office is warmer than the temperature of the air at the same height in the south-facing office. The occupants of NH4 and SH1 operated their space similarly during the working hours (one open window and door open). The only difference in the operation of the spaces is that in SH1 lights were off almost continuously during occupied hours, whereas in NH4 the light was constantly on.

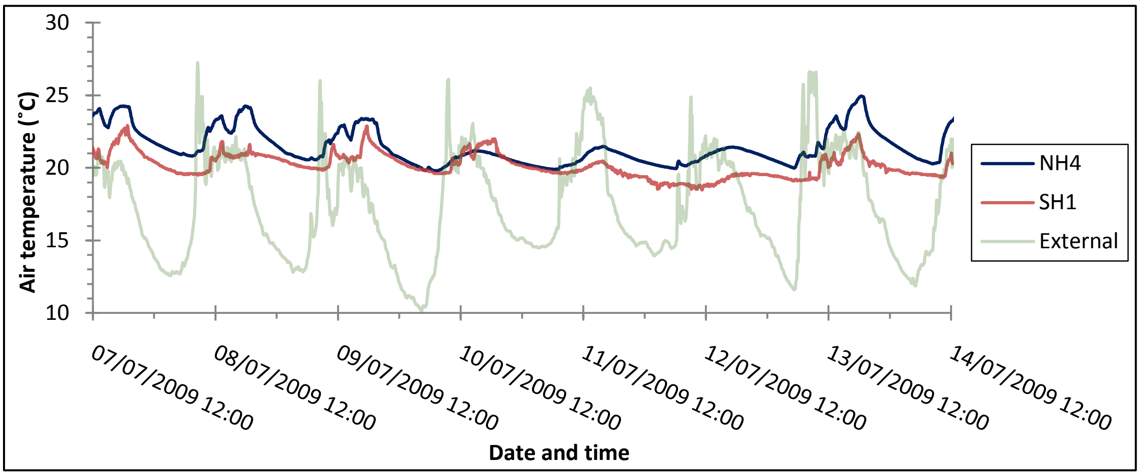

Figure 5.8: Diurnal temperatures for the south and north facing heavyweight single-occupancy offices.

Both offices have 25% of their external wall glazed. Since they both had their windows open a little, heat lost through the windows could be different depending on the direction of the wind; if the wind direction was south-west the south-facing office would cool down more than the north-facing office. Further, the south-facing office has external shading (due to the extended roof) blocking sunlight from entering the office, which makes it behave more like a north-facing office. Unluckily, during this period of summer monitoring it was mostly cloudy and raining, hence during the heat-wave week the office could have behaved differently.

Multi-occupancy offices, with the same thermal mass, had a very similar indoor air temperature despite their orientation (heavyweight north and south: r = 0.878, $p < 0.001$; lightweight north and south r= 0.913, $p = 0.001$) (Table 5.4 and Figure 5.9).

Table 5.4: Summer indoor air temperatures for multi-occupancy offices of different thermal mass.

Multi-occupancy 22/06/09 – 03/07/09 / Orientation	Indoor air temperature during working period (9am-6pm) (˚C)			Indoor air temperature (24hr) (˚C) (%RH)			Corresponding outdoor air temperature for $T_{in\ (9am\ -6pm)}$ (˚C)			Correlation of indoor air temperature and outdoor air temperature
	Av	Max[i]	Min[i]	Av	Max	Min	Av	$T_{time\ max}$[i]	$T_{time\ min}$[i]	
SL5	25.6	32.6	19.6	25.0 (49.6)	32.6 (31.9)	19.5 (45.4)	22.4	30.7	14.3	Moderate (r = 0.670, p < 0.001) (r^2 = 0.449, p < 0.001)
NL1	25.9	33.0	16.3	24.8 (51.0)	33.0 (35.7)	16.0 (67.4)	22.4	30.1	14.1	Strong (r = 0.719, p < 0.001) (r^2 = 0.517, p < 0.001)
SH2	24.2	28.0	21.5	23.8 (52.3)	28.0 (38.6)	21.2 (55.6)	22.4	30.8	19.8	Moderate (r = 0.692, p < 0.001) (r^2 = 0.479, p < 0.001)
NH6	23.9	26.8	20.6	23.4 (55.6)	26.8 (43.5)	20.6 (54.8)	22.4	30.8	14.4	Strong (r = 0.749, p < 0.001) (r^2 = 0.561, p < 0.001)

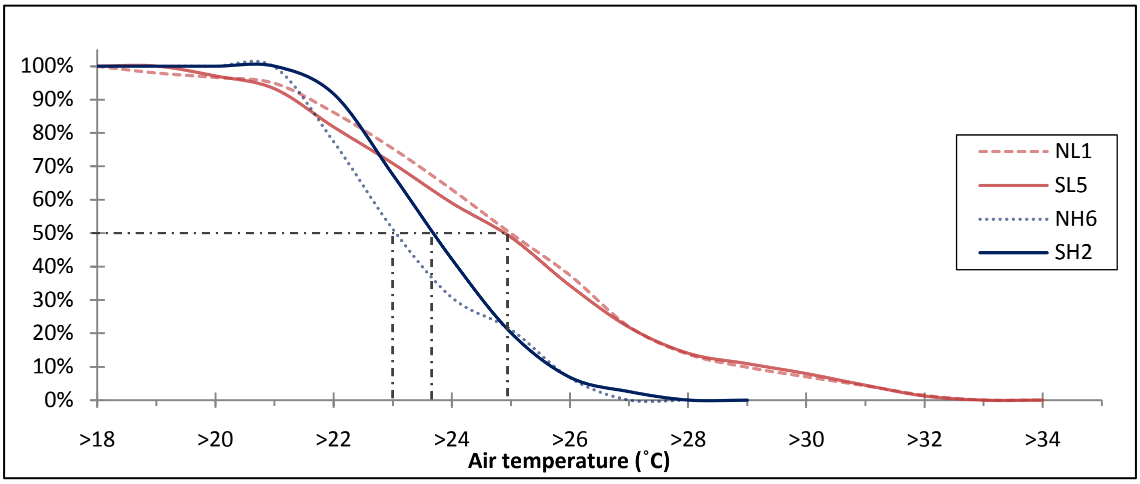

Figure 5.9: Summer temperatures for multi-occupancy offices during the heat-wave.

From Figure 5.9, it can be observed that the maximum and minimum indoor air temperatures of NH6 (T_{max} = 26.8°C, T_{min} = 20.6°C), were only slightly lower than the corresponding temperatures reached in SH2 (21.2°C to 28.0°C), despite SH2 receiving sunlight for the majority of the day and has 20% more glazing on its two external walls. Perhaps the reason is because NH6 rarely has its door open hence the heat stays in the room.

On the contrary, NL1 had an insignificantly higher maximum air temperature (33.0°C) than SL5 (32.6°C). Regardless of their thermal mass, the north-facing office has a stronger correlation with the outdoor air temperature than the south-facing office. This could be attributed to the fact that in SL5 there were less occupants at any given time (one to two people on average) than in NL1 (three to four people). Although it appears that the orientation of multi-occupancy offices does not have a significant effect on the indoor air temperatures (Table 5.4), this cannot be concluded with confidence (different number of people in each office, different operation of spaces and small sample).

Indoor air temperatures in single-occupancy offices of different orientations and of different thermal mass (Table 5.2) show that office NH2 has the lowest mean indoor air temperature and the smallest range. SL1 and WL1 follow the same temperature pattern, with SL1 having almost a constant 2˚C higher air temperature than WL1. SL1 reached a maximum temperature of 36˚C, whereas WL1 reached a maximum of 33˚C. Comparing these two worst case scenarios to the best case, which is office NH2 (max $T_{max\ in}$ = 28˚C), results in a difference of 8˚C for SL1 and 6˚C WL1. Various factors can account for this noticeable difference. The lowest temperature was reached in a heavyweight office, having 25% of its external wall glazed (whereas the other had 50%), and was not receiving direct solar radiation. They all operated their spaces similarly (open door and two windows open) hence the difference in the indoor air temperatures in this case cannot be attributed to different operations of the spaces alone.

Nevertheless, the extent of influence of the outdoor air temperatures on the indoor air temperatures varies from office to office, with the largest influence being in office EL1 (76%), followed by office SL1 (51%), and lastly by WL1 (45%) (Table 5.4). The summer indoor air temperatures of the lightweight offices were affected by the tree in the courtyard. The tree was nearer to the west side of the building than the east or south facades. Consequently, it is highly likely that the shading contributed to the lower indoor air temperatures of office WL1.

Offices SL1 and EL1 did not have any shading from the tree and therefore the indoor air temperatures they reached are due to other factors.

The amount of influence of outdoor air temperature to the indoor seems to be largely affected by the adaptive opportunities used by the occupants. For example, the occupant of EL1 had the door closed and only one of the two possible windows open. The occupant of SL1 had two windows open with a partly opened door and a fan, whereas the occupant of WL1 had both possible windows open, the door fully open, and a fan. The more air movement (speed and cross-ventilation), the lower the indoor air temperature due to air exchanges with lower temperature sources. (This is further explained in Section 5.1.4.)

5.1.2.3 Occupancy Levels

Offices of different occupancy levels have significantly different indoor air temperatures even if they have the same orientation and have the same thermal mass (e.g. heavyweight north t = -21.8, p < 0.001) (Figure 5.10). At the beginning of the monitoring period the single-occupancy north-facing heavyweight office (NH2) is cooler than the multi-occupancy (NH6) (on average ΔT = 1°C during day-time and ΔT = 2°C at night-time). This is expected as the multi-occupancy office is more densely populated and therefore there are more heat gains during daytime per meter squared. As the outdoor air temperatures increase (above 28°C), NH2 gets warmer than the multi-occupancy often during the day-time (on average ΔT = 1°C), but reach the same minimum temperature over night-time. The single-occupancy often reaches its maximum temperature after the multi-occupancy office (within one hour), and has greater amplitude in its indoor air temperatures (NH2: T_{max} = 4°C, NH6: T_{max} = 2°C). The higher variation is believed to be partly related to the heat exchanges occurring through the exposed roof of NH2.

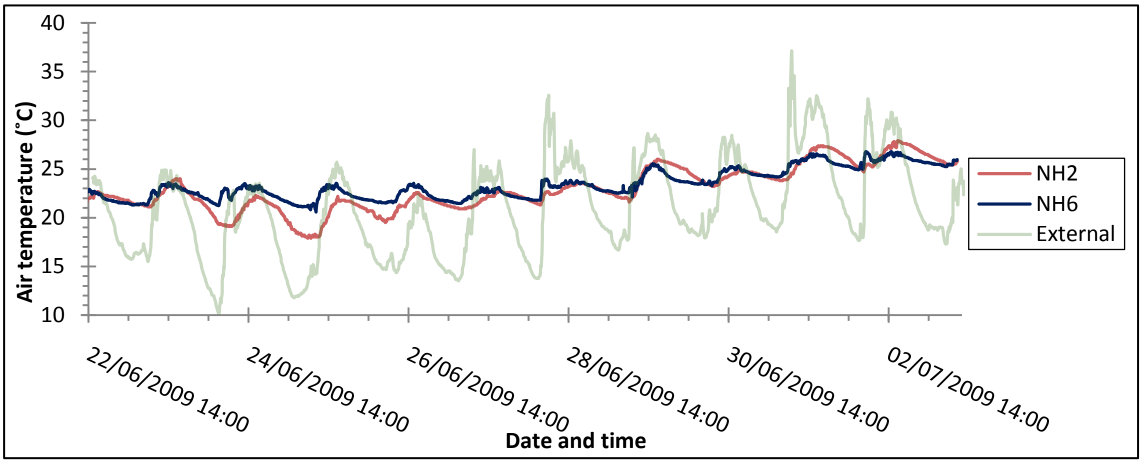

Figure 5.10: Comparison of indoor temperatures for heavyweight offices with different occupancy levels.

The lightweight south-facing offices of different occupancy levels follow a very similar diurnal cycle (Figure 5.11). However, maximum indoor air temperatures are higher for the single-occupancy office (SL1) than for the multi-occupancy office (SL5) (on average ΔT = 2.5°C), despite being reached at almost the same time. The two offices are located next to each other, but the occupants of SL5 had their doors and windows open allowing for cross-ventilation, unlike the occupant of SL1 who had the door closed most of the time.

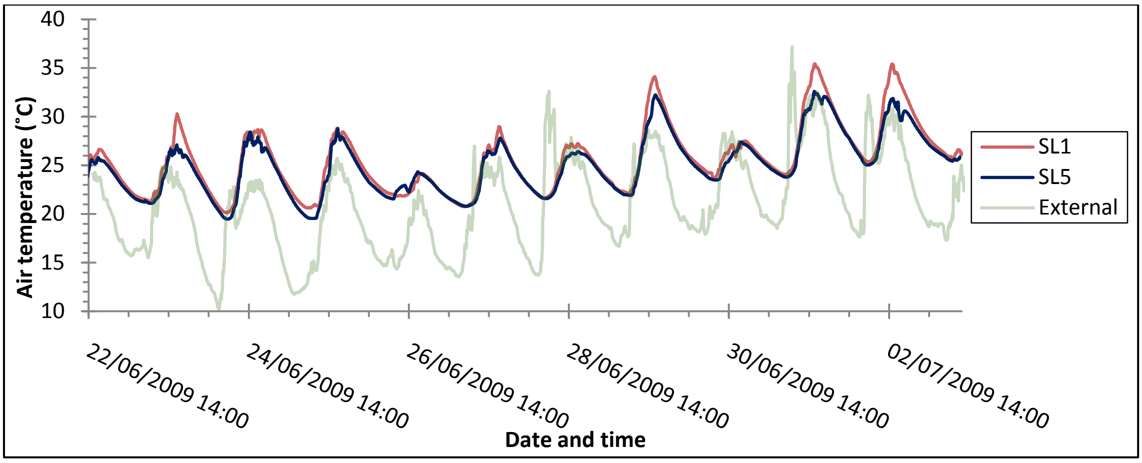

Figure 5.11: Comparison of indoor temperatures for lightweight offices with different occupancy levels.

5.1.2.4 Space Operation

The strength of correlation between indoor and outdoor air temperatures vary from office to office, even for the ones having the same orientation and thermal mass. Lightweight offices monitored in the second summer phase (SL2, SL3 and SL4) were all facing in the same direction, but the maximum and minimum air temperatures were different[vi] (Table 5.3 and Figure 5.12). The peak temperatures were reached by a different office on each monitoring day, indicating that office size and the amount of glazing was not as influential on the indoor air temperature as the operation of the office by its occupants.

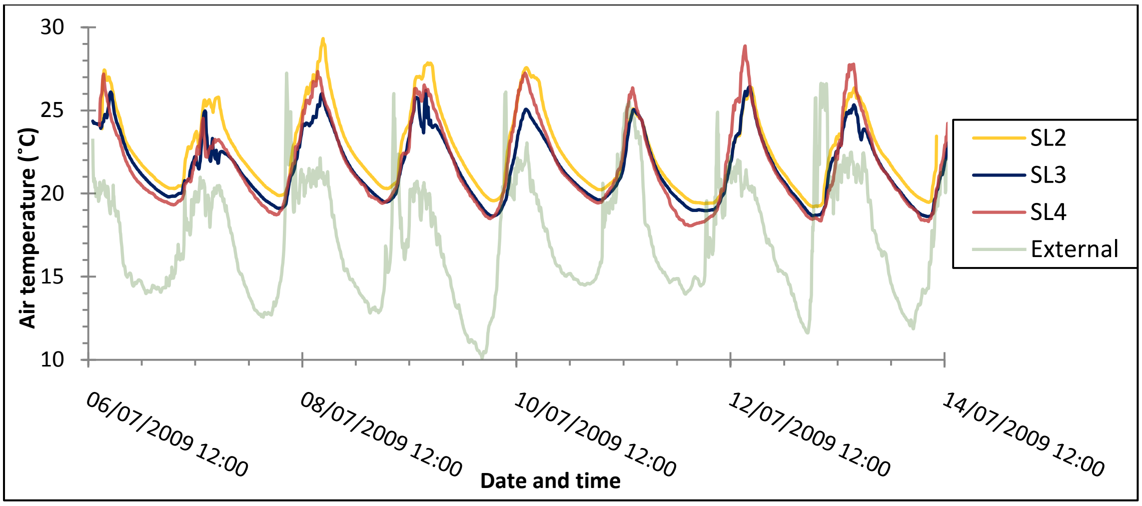

Figure 5.12: Diurnal temperatures for the south-facing single occupancy lightweight offices.

The variance in indoor air temperatures caused by the changes in the outdoor air temperatures for the heavyweight offices is not high (4% – 17%) when compared to that for the lightweight offices (30 – 60%). Outdoor air temperatures seem to have more influence on the indoor air temperatures for the lightweight offices than for the heavyweight offices, which is expected due to its lower thermal capacity. Further, the indoor temperatures reached by the south-facing lightweight offices (T_{av} = 24˚C, and T_{max} = 29˚C), are higher than the ones reached by the south-facing heavyweight office, indicating the relationship between indoor air temperature and thermal mass. Similarly, spring indoor air temperatures of offices follow the same indoor air temperature diurnal pattern (Table 5.5) as expected, yet the mean indoor air temperature

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[vi] Performed t-test on the various combinations and in all cases $p < 0.001$, suggesting that the mean indoor air temperatures for those offices are significantly different.

of each office is significantly different between the offices compared. This is believed to be attributed once again to the different operation of the spaces by each occupant.

Table 5.5: Correlation between the indoor air temperatures of similar offices.

Single-occupancy			Correlation between indoor air temperatures	Significant difference between the mean indoor air temperatures
Thermal mass	**Monitoring period**	**Office**		
Lightweight	20/03/09 – 20/03/09	WL1 – WL5	Strong (r = 0.864, $p < 0.001$)	Significant difference ($t = -36.5$, $p < 0.001$)
	23/03/09 – 25/03/09	WL1 – WL2	Strong (r = 0.726, $p < 0.001$)	Significant difference ($t = -32.3$, $p < 0.001$)
	06/05/09 – 13/05/09	WL1 – WL5	Strong (r = 0.918, $p < 0.001$)	Significant difference ($t = -96.6$, $p < 0.001$)
Heavyweight	26/03/09 – 27/03/09	NH5 – NH3	Strong (r = 0.717, $p < 0.001$)	Significant difference ($t = 12.8$, $p < 0.001$)
	28/04/09 – 01/05/09	NH5 – NH4	Moderate (r = 0.677, $p < 0.001$)	Significant difference ($t = 31.4$, $p < 0.001$)

Some offices monitored more than once over the spring period show different indoor air temperatures, with correlations between indoor and outdoor air temperatures varying from moderate to strong (Table 5.6).

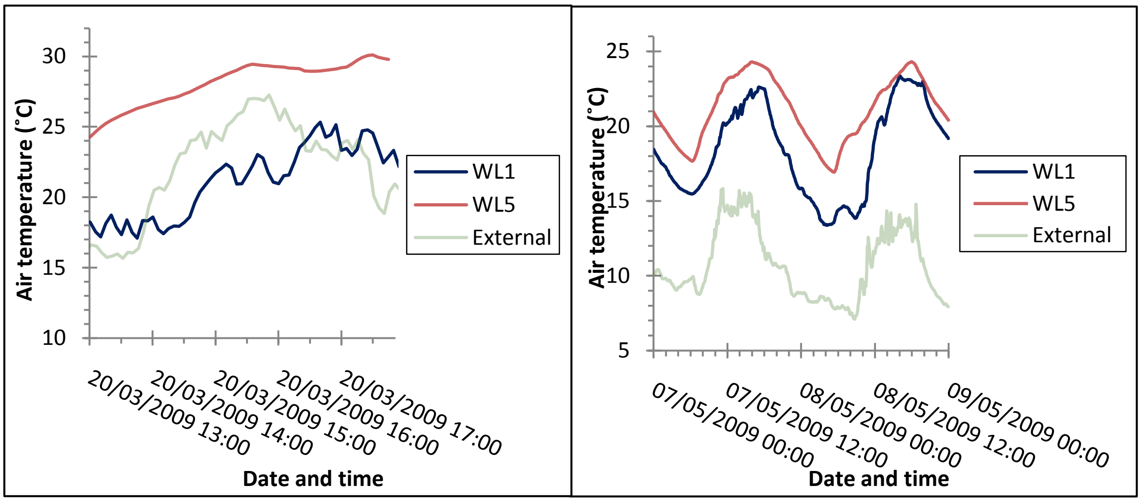
Table 5.6: Air-temperatures for the spring monitoring period of single occupancy offices.

Single-occupancy		Indoor air temperature (9am-6pm) (˚C) (% RH)			Corresponding outdoor air temperature to $T_{in\ (9am\ -6pm)}$ (˚C)			Correlation of indoor air temperature and outdoor air temperature
Monitoring period	**Office**	Av	Max	Min	Av	$T_{time\ max}$	$T_{time\ min}$	
20/03/09 – 20/03/09	WL1	21.1 (30.8)	25.3 (24.5)	17.1 (34.7)	16.8	23.4	16.4	Moderate (r = 0.569, $p < 0.001$, $r^2 = 0.324$, $p < 0.001$)
	WL5	28.1 (26.7)	30.1 (20.4)	24.3 (32.8)	16.8	20.1	16.6	Strong (r = 0.758, $p < 0.001$, $r^2 = 0.574$, $p < 0.001$)
23/03/09 – 25/03/09	WL1	20.8 (36.7)	26.7 (25.9)	15.7 (40.9)	9.95	11.3	11.4	Moderate (r = 0.494, $p < 0.001$, $r^2 = 0.244$, $p < 0.001$)
	WL2	24.6 (30.9)	28.0 (23.8)	19.8 (34.9)	9.95	14.3	9.94	Weak (r =0.204, $p < 0.001$, $r^2 = 0.042$, $p < 0.001$)
06/05/09 – 13/05/09	WL1	21.5 (40.1)	27.4 (28.8)	13.9 (53.8)	11.9	18.2	7.39	Strong (r = 0.783, $p < 0.001$, $r^2 = 0.614$, $p < 0.001$)
	WL5	23.7 (36.9)	28.3 (32.5)	19.5 (41.6)	11.9	22.0	7.39	Strong (r = 0.762, $p < 0.001$, $r^2 = 0.580$, $p < 0.001$)
26/03/09 – 27/03/09	NH5	24.3 (34.1)	28.8 (30.2)	21.1 (44.6)	7.82	12.1	10.5	Strong (r = 0.784, $p < 0.001$, $r^2 = 0.615$, $p < 0.001$)
	NH3	23.4 (36.1)	25.0 (38.8)	21.4 (34.6)	7.82	10.5	6.90	Strong (r = 0.921, $p < 0.001$, $r^2 = 0.848$, $p < 0.001$)
28/03/09 – 02/04/09	NH3	20.2 (36.4)	23.7 (37.4)	15.8 (34.4)	8.63	16.1	5.10	Strong (r = 0.709, $p < 0.001$, $r^2 = 0.503$, $p < 0.001$)
28/04/09 – 01/05/09	NH4	20.5 (45.4)	22.2 (50.3)	18.2 (44.0)	12.0	15.8	11.9	Moderate (r = 0.627, $p < 0.001$, r^2 =0.393, $p < 0.001$)
	NH5	23.9 (35.5)	28.8 (29.5)	19.5 (38.4)	12.0	16.4	13.6	Moderate (r = 0.355, $p < 0.001$, $r^2 = 0.126$, $p < 0.001$)
02/05/09 – 06/05/09	NH5	19.7 (41.6)	25.2 (38.4)	17.8 (43.2)	12.1	15.1	12.2	Moderate (r = 0.450, $p < 0.001$, $r^2 = 0.202$, $p < 0.001$)

For example, the occupant of NH3 has almost perfect correlation (r = 0.921) between the indoor and outdoor air temperatures during the 26/03/2009 – 27/03/2009 monitoring period. However, during the monitoring period 28/03/2009 – 02/04/2009, the correlation is slightly weaker (r = 0.709), suggesting that the heat flow between the internal and external walls is influenced by the operation of the spaces as well as the environmental conditions (including varying solar gains). The different relationships between the indoor and outdoor air temperatures over different months of monitoring, for the same offices, is believed to be due to the different operational habits of the occupants, the auxiliary heating and the operation of any additional fans / heaters.

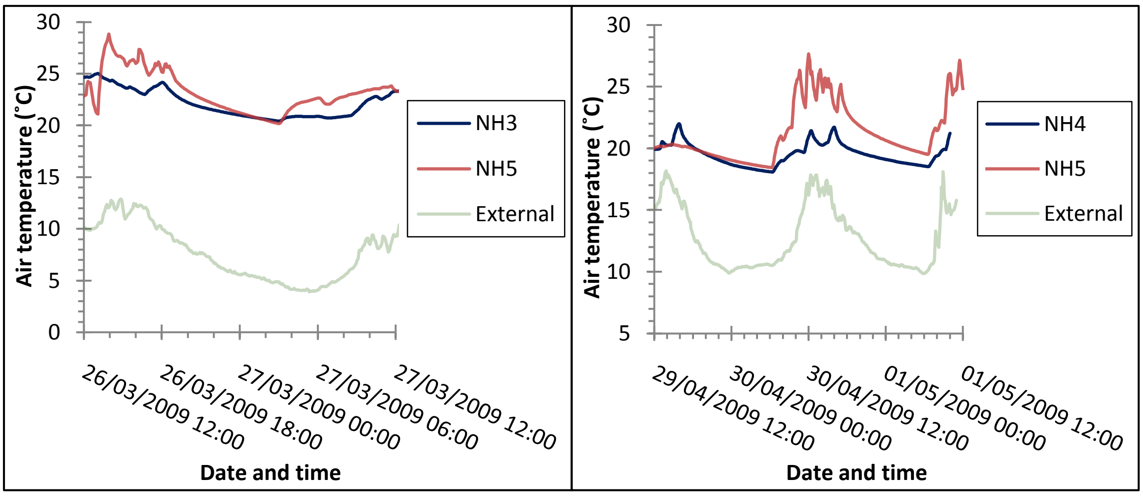
5.1.2.5 Gender

Although based on a small sample, the results suggest that women maintain higher indoor air temperatures in their offices when compared to identical offices occupied by men, in both the lightweight building (Figure 5.13) and the heavyweight building (Figure 5.14).



March monitoring May monitoring

Figure 5.13: Indoor air temperatures of lightweight offices (for male and female sample) for March and May.



March monitoring April monitoring

Figure 5.14: Indoor air temperatures of heavyweight offices (for male and female sample) for March and April / May.

When analyzing WL1's and WL5's indoor air temperatures for May, WL5's has almost a constant 3˚C higher temperature than WL1's, with the maximum and minimum temperatures being reached at the same time (Figure 5.13). This constant difference is attributed to the fact that the occupant of WL1 had the office windows open for most of the occupied time, whereas the occupant of WL5 had them closed. WL5 was a female occupant, whereas WL1 was a male occupant and although this is based on a very small sample, it might be due to males operating their spaces differently from females.

For the heavyweight offices, although during day-time the air temperature in the female office is higher than in the one occupied by the male occupant, during night-time the temperatures drop, causing a temperature difference of less than 0.5˚C. This is unlike the lightweight offices which have a constant difference throughout the day and night. The difference between indoor and outdoor air temperatures at night-time for the heavyweight offices is 14 – 15°C (Figure 5.14), whereas for the lightweight office is on average 11°C for similar spring conditions. During day-time, the difference between indoor and outdoor air temperatures varies depending on the operation of the spaces by their occupants.

5.1.3 Winter and Autumn Monitoring

The winter and autumn study were undertaken in two single-occupancy lightweight west-facing offices and two north-facing heavyweight offices, and in two heavyweight multi-occupancy offices located in opposite orientations (south and north). These monitorings were carried out for a longer period than the spring and summer monitorings. The findings are described below in the relevant subsections.

5.1.3.1 Building's Thermal Mass

The indoor average air temperature for single-occupancy heavyweight offices varies between autumn and winter seasons by 2˚C (Table 5.7), unlike for the lightweight offices which have a variance of less than 1˚C (Table 5.8).

Table 5.7: Summary of autumn/winter monitoring of heavyweight single-occupancy offices.

Heavyweight Single-occupancy North-facing		**Indoor air temperature (24hr) (˚C) (%RH)**			**Corresponding outdoor air temperature for indoor air temperature (˚C)**			**Correlation of indoor air temperature and outdoor air temperature**	**Carbon dioxide level (ppm)**		
Monitoring period	**Office**	Av	Max	Min	Av	$T_{time\ max}$	$T_{time\ min}$		Av	Max	Min
14/10/08 – 14/11/08	NH1	18.7 (52.3)	23.7 (54.7)	14.2 (51.3)	9.20	13.2	9.07	Moderate ($r = 0.448$, $p = 0.001$) ($r^2 = 0.201$, $p = 0.001$)			
	NH2	19.6 (48.9)	25.1 (45.3)	13.5 (51.4)	9.20	12.3	6.73	Moderate ($r = 0.332$, $p < 0.001$) ($r^2 = 0.110$, $p < 0.001$)			
15/11/08 – 01/12/08	NH1	18.2 (47.3)	22.8 (48.2)	12.2 (42.3)	6.70	11.5	1.52	Strong ($r = 0.711$, $p = 0.001$) ($r^2 = 0.505$, $p = 0.001$)	470	1590	350
	NH2	18.4 (44.5)	23.3 (48.5)	9.85 (49.7)	6.70	10.0	2.67	Moderate ($r = 0.576$, $p = 0.001$) ($r^2 = 0.332$, $p = 0.001$)	480	1330	370

Table 5.7 continued.

28/01/09 – 09/02/09	NH1	17.0 (35.8)	22.4 (36.7)	13.2 (35.7)	1.72	5.20	2.97	Moderate (r = 0.513, *p* = 0.001) (r^2 = 0.263, *p* = 0.001)	495	1710	390
	NH2	17.9 (32.6)	23.9 (39.1)	12.5 (35.6)	1.72	8.60	2.97	Weak (r = 0.279, *p* = 0.001) (r^2 = 0.078, *p* = 0.001)	435	1245	345

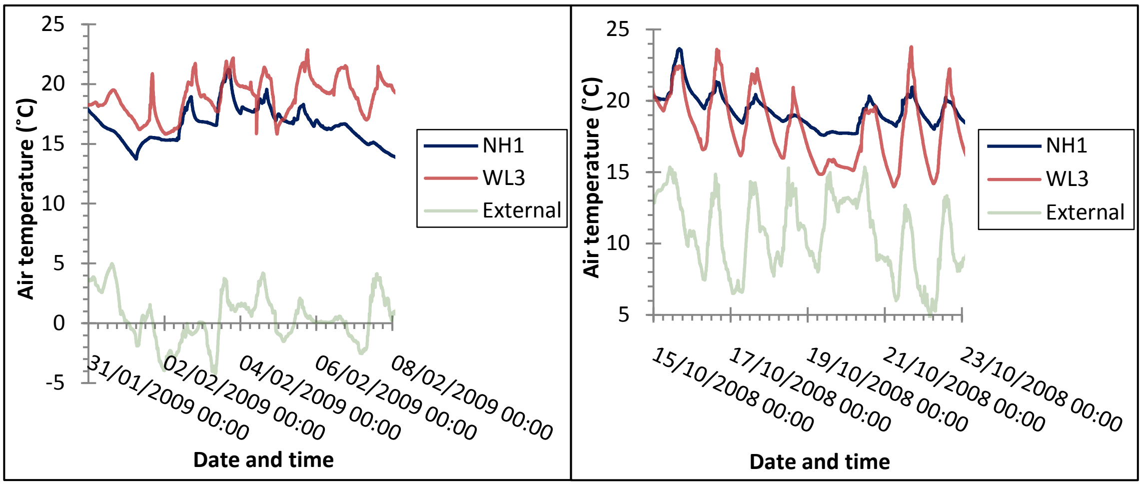
Table 5.8: Summary of autumn/winter monitoring of lightweight single-occupancy offices.

Lightweight Single-occupancy West-facing		**Indoor air temperature (24hr) (˚C) (%RH)**			**Corresponding outdoor air temperature for indoor air temperature (24hr) (˚C)**			**Correlation of indoor air temperature and outdoor air temperature**	**Carbon dioxide level (ppm)**		
Monitoring period	**Office**	Av	Max	Min	Av	$T_{\text{time max}}$	$T_{\text{time min}}$		Av	Max	Min
14/10/08 – 14/11/08	WL3	18.8 (48.7)	26.3 (40.3)	10.9 (64.2)	9.21	8.96	7.03	Weak (r = 0.257, *p* = 0.001) (r^2 = 0.066, *p* = 0.001)	615	1255	390
	WL4	19.1 (47.5)	28.0 (40.6)	11.1 (65.0)	9.21	12.9	7.03	Moderate (r = 0.422, *p* = 0.001) (r^2 = 0.178, *p* = 0.001)	540	1730	360
15/11/08 – 21/11/08	WL3	18.8 (52.6)	25.1 (42.0)	14.0 (58.8)	9.72	8.04	7.45	Weak (r = 0.186, *p* = 0.001) (r^2 = 0.035, *p* = 0.001)	535	1195	390
	WL4	18.5 (54.0)	24.0 (43.1)	13.9 (61.2)	9.72	10.5	7.44	Weak (r = 0.235, *p* = 0.001) (r^2 = 0.055, *p* = 0.001)	460	1350	360
28/01/09 – 09/02/09	WL3	19.3 (31.7)	24.5 (39.6)	15.8 (26.2)	1.72	7.45	-3.23	Moderate (r = 0.474, *p* = 0.001) (r^2 = 0.225, *p* = 0.001)	460	1189	346
	WL4	18.9 (31.3)	22.6 (44.2)	15.7 (44.0)	1.72	8.01	-3.56	Moderate (r = 0.573, *p* = 0.001) (r^2 = 0.328, *p* = 0.001)	475	1051	393

The monitoring data suggests that there is no influence of outdoor air temperature on indoor air temperature in either buildings. This is believed to be due to the auxiliary heating being operated on some days (e.g. on weekdays but not on weekends) and hence the building is sometimes free-run, and other days artificially heated. Furthermore, the different operations of windows and doors of the occupant, contributes to these differences.

North-facing heavyweight offices have lower maximum temperatures over autumn (~3°C) (Figure 5.15) and over early-winter (15/11/2008 – 01/12/2008) (~1.5°C) (Tables 5.7 and 5.8) than the west-facing lightweight offices, even though they have the same average temperatures. This is not just attributed to the different thermal mass of the offices, but also to the different orientation of the offices, as the west-facing offices receive direct sunlight unlike the north-facing offices.

On comparing the daily indoor air temperature of NH1 with WL3 for the October monitoring (Figure 5.15), it is observed that there is a lower range for the heavyweight (ΔT_{max} = 5˚C) than for the lightweight (ΔT_{max} = 10˚C). This difference in variation was also noted in the summer findings, suggesting that the heavyweight office is more stable than the lightweight office. The indoor air temperatures of the heavyweight offices (T_{max} = 25.1˚C) were lower in mid-October than the temperatures recorded for the lightweight (T_{max} = 28.0˚C). Orientation of the offices was also contributing to this difference, apart from the different thermal mass, and the different adaptive opportunities of the spaces. The heavyweight offices were north-facing, and hence received no direct solar radiation, in contrast to the lightweight west-facing offices that received solar radiation every afternoon.



Autumn Winter

Figure 5.15: Comparing indoor air temperatures for the heavyweight and lightweight offices for autumn and winter monitoring.

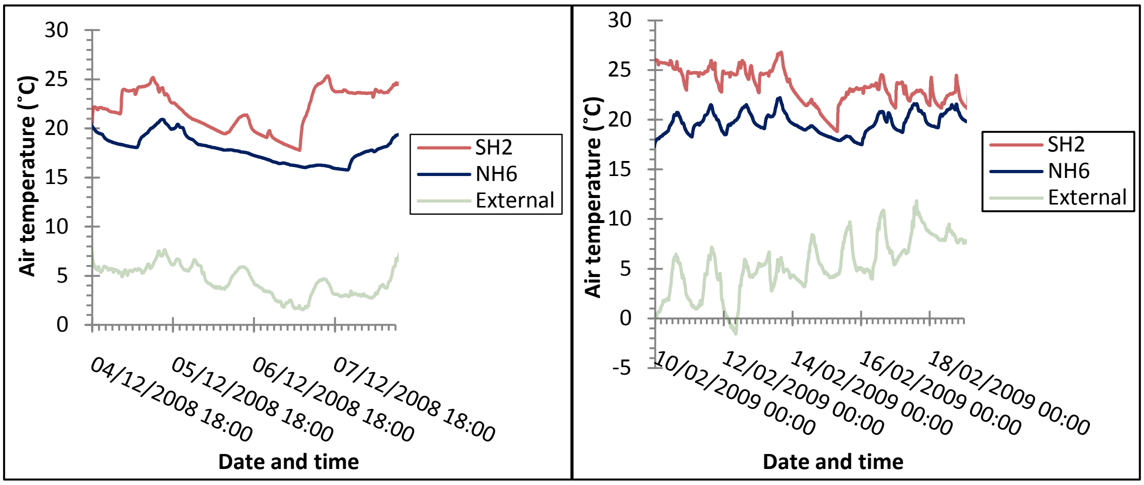
Although both sets of offices were within the comfort range during the mornings (at around 9am), the temperature rose rapidly for the lightweight office, reaching a much higher value, even though the lightweight building had a heating set-point 1°C lower than the heavyweight building, and was starting every morning a half to one hour later than for the heavyweight building. The peak temperature for the heavyweight office was reached before the peak temperature for the lightweight office and this could be due to the operation of the spaces by the occupants (opening the windows and doors for short periods to let fresh air in and heat out; seen as flat small peaks in the lightweight temperature lines of Figure 5.15). This cannot be due to the thermal capacity of the fabric as the higher it is the more slowly it absorbs heat and should reach peak temperature later.

When the buildings were free-run such as on the 19th October 2008 (Sunday), the heavyweight offices had a higher indoor air temperature during day-time than the lightweight offices, despite the different orientation (Figure 5.15). The thermal mass of the heavyweight office was releasing heat hence the difference between the indoor and outdoor temperature was 3°C, making the indoor air temperature (18°C) just below the suggested minimum of 19°C. The lightweight offices were directly affected by the outdoor air temperature (just 1˚C warmer).

During the mid-winter monitoring, the heavyweight office is almost constantly cooler than the lightweight office, and likewise to the other seasons the diurnal variation in the indoor temperature is less than for the lightweight offices (Figure 5.15). As expected, the lightweight office responds more quickly than the heavyweight office to the auxiliary heating, and at night it loses heat more quickly than the heavyweight offices.

5.1.3.2 Office Orientation

The results of heavyweight multi-occupancy offices in winter (orientated in opposite directions; NH6 and SH2), suggests that the south-facing office is constantly warmer than the north-facing office whether free-running (weekends e.g. 06/12/2008 – 07/12/2008, 14/02/2009 – 15/02/2009) or artificially heated (weekdays) (Figure 5.16). When the building is free-run, the difference between the indoor air temperatures between the two opposite facing offices (SH2 and NH6) decreases to less than a 2°C difference. It can thus be concluded that for both seasons (summer and winter), the south-facing offices are warmer than the north-facing multi-occupancy office.



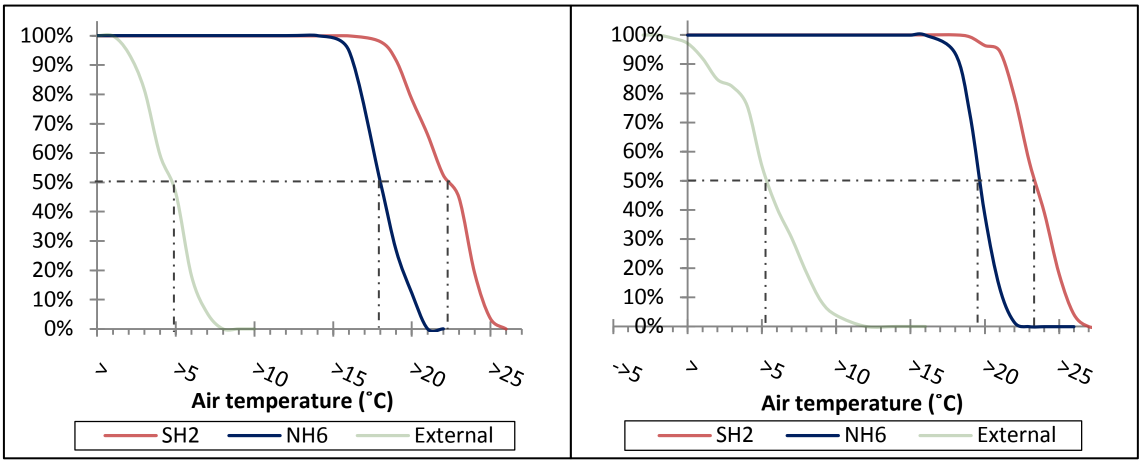
Early winter Late winter

Figure 5.16: Diurnal temperature for heavyweight multi-occupancy offices in early and late winter.

The sudden increases in the indoor air temperature of SH2 over the weekends correspond with a student coming into the office. The student was coming to the office on Saturdays (e.g. 06/12/2008) and Sundays (e.g. 07/12/2008) and was working until 18.00 on some occasions. For example on the 07/12/2008 the room was occupied by one of the students since 5.30am, and hence there is a sharp increase (2°C) in the indoor air temperature by 8.00am (due to electrical equipment / PC, heat gains from the occupant, and a personal portable heater). Over the December monitoring period, there is a significant difference in the indoor air temperatures for the two multi-occupancy offices ($t = 63.8$, $p = 0.001$) (Figure 5.16) with north-facing office being constantly colder than the south-facing office.

During the February monitoring there is once again a constant difference between the air temperature difference of the two offices, with the south-facing office being significantly warmer than the north-facing office ($t = 110$, $p = 0.001$) (Figure 5.17). The offices have the same indoor temperature pattern with a delay of a maximum of four hours for the north-facing office. The diurnal air temperature of the two offices does not have the distinctive peaks and troughs (Figures 5.16) like over the summer (Figures 5.5 and 5.6).

Throughout the coldest period of the winter monitoring (February) the indoor air temperatures were affected by 16 – 17% by the outdoor temperatures despite the orientation of the offices (as depicted by the r^2 value in Table 5.9). It was continually cloudy and snowing during this monitoring period and hence both offices had the same indoor-outdoor temperature correlations, as all other heat gains were the same.



04/12/08 – 08/12/08 09/02/09 – 19/02/09

Figure 5.17: Indoor air temperatures for December monitoring of heavyweight multi-occupancy offices.

Over the monitoring in December, the variance of the indoor air temperature caused by the variance in the outdoor air temperature is significantly different for the south-facing office (16%) compared to that of the north-facing (72%). This difference cannot be attributed to window operations, as both offices had their windows continuously closed hence it is due to the number of occupants that were present in the offices affecting also the number of computers switched on (over the two working days there were three to four more occupants in SH2 than in NH6, and over the weekend there was one occupant in the south-facing but no occupants in the north-facing office, who was using a portable heater). Further the south-facing office had solar gains, increasing the indoor air temperature at a faster rate than for the north-facing office.

Table 5.9: Winter temperatures for heavyweight multi-occupancy offices.

Heavyweight Multi-occupancy		Indoor air temperature (24hr) (˚C)			Corresponding outdoor air temperature for indoor air statistics (˚C)			Correlation of indoor air temperature and outdoor air temperature
Monitoring period	**Orientation**	Av	Max	Min	Av	Max	Min	
04/12/08 – 08/12/08	SH2	22.1	25.4	17.8	4.58	4.32	1.94	Moderate ($r = 0.405$, $p = 0.001$) ($r^2 = 0.164$, $p = 0.001$)
	NH6	18.0	20.9	15.8	4.58	7.06	2.94	Strong ($r = 0.849$, $p = 0.001$) ($r^2 = 0.721$, $p = 0.001$)
09/02/09 – 19/02/09	SH2	23.4	26.8	18.8	5.40	6.04	4.38	Moderate ($r = -0.423$, $p = 0.001$) ($r^2 = 0.179$, $p = 0.001$)
	NH6	19.7	22.7	17.2	5.40	5.79	0.33	Moderate ($r = 0.411$, $p = 0.001$) ($r^2 = 0.169$, $p = 0.001$)

5.1.3.3 Occupancy Levels

During winter, the single- (NH1 and NH2) and multi-occupancy (NH6) heavyweight north-facing offices were not monitored over the same period. However, since they were monitored over the same months the temperatures were similar and hence comparisons will be made (December: $\Delta T_{\text{av out}}$ = 2°C – warmer for single-occupancy; February: $\Delta T_{\text{av out}}$ = 4°C – warmer for multi-occupancy). It appears that for the heavyweight offices occupancy levels do not have a significant effect on average indoor air temperatures over early winter (multi T_{av} = 18.0°C, single T_{av} = 18.3°C) (Tables 5.7 and 5.9). Over the 'unusual' cold winter, the multi-occupancy office was on average warmer than the single-occupancy offices (multi T_{av} = 19.7°C, single T_{av} = 17.5°C), due to the higher outdoor temperature and more equipment switched on. Yet, they all reached a similar maximum temperature (multi T_{max} = 22.7°C, single T_{max} = 23.1°C) (Tables 5.7 and 5.9).

Over the winter monitoring period the occupants of NH1 and NH2 (single-occupancy) had their window open for an average of 28.6% of the time that they were present in their office. The occupants of NH6 (multi-occupancy) had opened their window only 0.1% of the monitoring time. Consequently, it is expected that the multi-occupancy offices are going to have a higher average temperature. (The operation of windows and doors is discussed later in Section 5.1.4.)

5.1.3.4 Space Operation

The indoor air temperatures of offices of the same thermal mass and same orientation were correlated and it was discovered that they behave almost similarly at the same time but they have significantly different indoor air temperatures (Table 5.10).

Table 5.10: Comparing indoor air temperatures for offices of the same orientation for autumn and winter.

Single-occupancy		Correlation between indoor air temperatures	Significant difference between the mean indoor air temperatures
Office	**Monitoring period**		
WL3 – WL4	14/10/08 – 14/11/08	Strong (r = 0.937, p = 0.001)	Significant difference (t = -30.6, p = 0.001)
	15/11/08 – 01/12/08	Strong (r = 0.977, p = 0.001)	Significant difference (t = 16.1, p = 0.001)
	28/01/09 – 09/02/09	Strong (r = 0.928, p = 0.001)	Significant difference (t = 40.3, p = 0.001)
NH1 – NH2	14/10/08 – 14/11/08	Strong (r = 0.889, p = 0.001)	Significant difference (t = 84.6, p = 0.001)
	15/11/08 – 01/12/08	Strong (r = 0.914, p = 0.001)	Significant difference (t = 8.6, p = 0.001)
	28/01/09 – 09/02/09	Strong (r = 0.855, p = 0.001)	Significant difference (t = 38.0, p = 0.001)

The lightweight west-facing offices have large amplitudes in their indoor air temperatures (in some cases up to 14˚C). Although the average air temperatures are within the comfort range, the minimum temperatures are too low (as low as 14°C) (Figures 5.18 and 5.19). The maximum indoor air temperatures for the mid-autumn period (WL3: 26.3°C and WL4: 28.0°C) in the offices are higher than suggested by the Carbon Trust (2007), but for the late autumn and late winter (WL3: 24.5°C, and WL4: 22.6°C), although the indoor air temperatures are within the suggested range.

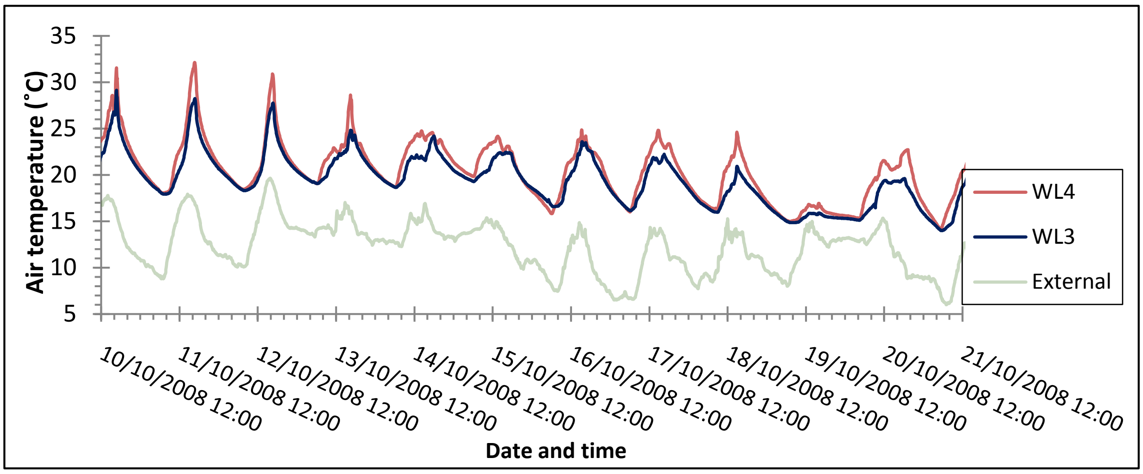


Figure 5.18: Diurnal autumn indoor air temperatures for the lightweight single-occupancy offices.

The transition from the minimum to maximum indoor air temperatures happens during working hours, and hence it is likely to affect the comfort of the occupants. In October, the heating (auxiliary) is turned on during occupied hours. On the 19/10/2008, which was a Sunday, the heating was not on at all in the offices, and so the lower peak indicates how the building copes during day-time without the heating on ($T_{max\ out}$ = 15°C , $T_{max\ in}$ = 16 –17°C) (Figure 5.18).

In the autumn study measurements of CO_2 levels in each office were taken. The maximum CO_2 levels were high (WL3: 1255, WL4: 1730ppm), with WL4 exceeding the suggested maximum levels (1400ppm) by BS EN 13779 (2007), which might make the indoor environment uncomfortable for the occupants. Office WL4 has higher CO_2 levels in autumn than its adjacent office WL3, where the occupant opens his window often but for short periods. The lower CO_2 level is also associated with the lower indoor air temperature. Similarly to the lightweight offices, the indoor maximum CO_2 levels are very high for the heavyweight offices (NH1: max CO_2 recorded 1710 ppm) (Table 5.7). The maximum CO_2 values were reached during lunchtime hours (1pm to 2pm) for the heavyweight offices and in the early afternoon (4pm to 5pm) for the lightweight offices.

The occupant of WL3 operates his window more often and still his office indoor air temperature is higher than the temperature reached in WL4 (Figure 5.19). For example, on the 30th of January the occupant of WL3 opened his window in the morning (10.15) for one minute and in the afternoon for thirty minutes (14.50). Despite the occupant of WL4 not operating his window on that day his indoor air temperature is 1 to 1.5°C lower than the indoor temperature reached in WL3, and this is believed to be due to the occupants adjusting the valve of their radiator. This difference cannot be attributed to WL4 being more leaky than WL3, e.g. through the windows, as on the weekends when the two offices were not occupied they had the same indoor air temperature. Further, this could be related to the number of hours the occupants were present in their office. The occupant of WL3 was in his office the majority of the day (left at 19.00), whereas the occupant of WL4 was in and out and left at 17.00. consequently the heat gains from the equipment and the human being in WL3 is expected to have an impact on the higher indoor air temperature reached in his office.

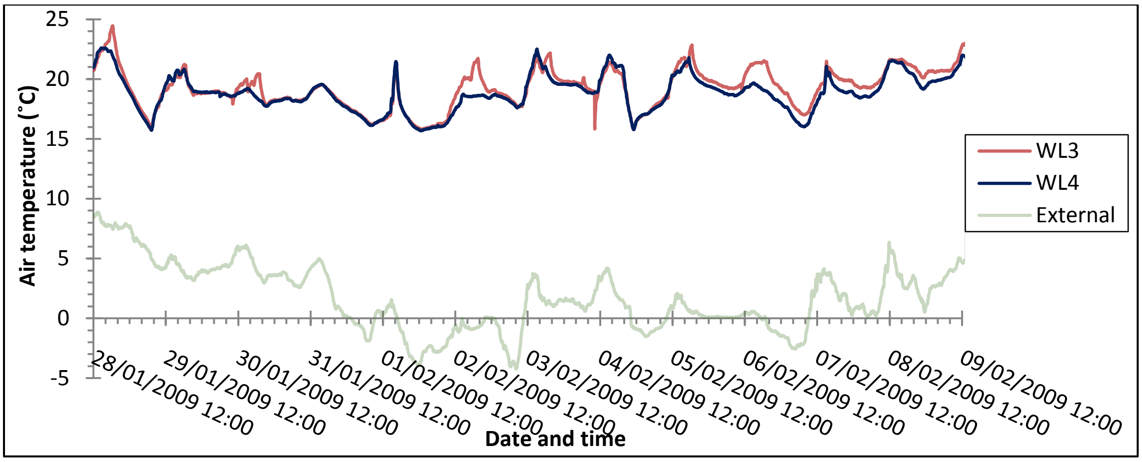


Figure 5.19: Diurnal winter indoor air temperatures for the lightweight single-occupancy offices.

During the cold-snap over winter (28/01/09 – 19/02/09 : outdoor air temperatures below 0°C), indoor air temperatures were within the comfort range (19 – 24°C) during working hours for the lightweight offices (Table 5.8). The 31/01/2009 (Saturday) – 01/02/2009 (Sunday), WL3 and WL4 have an identical indoor temperature swings, suggesting that the discrepancies in the indoor temperatures over the other days are caused by the operation of the spaces by the occupants.

The two heavyweight offices (NH1 and NH2) behave similarly thermally and have the same minimum air temperature for most of the night (Figures 5.20 and 5.21). Their peak indoor air temperatures are significantly different, with NH2 ($T_{max\ autumn}$ = 25˚C, $T_{max\ winter}$ = 24˚C) having almost always higher indoor air temperatures than NH1 ($T_{max\ autumn}$ = 23˚C, $T_{max\ autumn}$ = 22˚C).

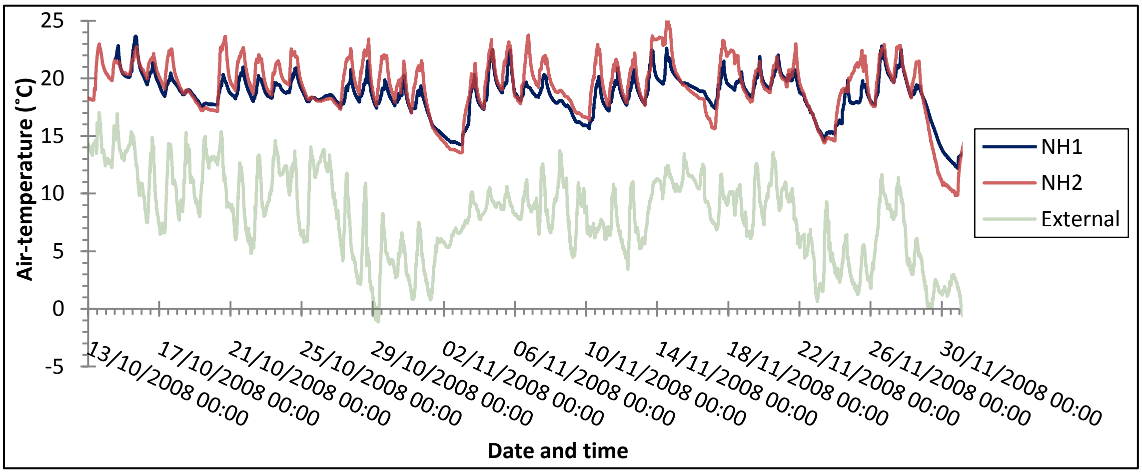


Figure 5.20: Diurnal autumn indoor air temperatures for the heavyweight single-occupancy offices.

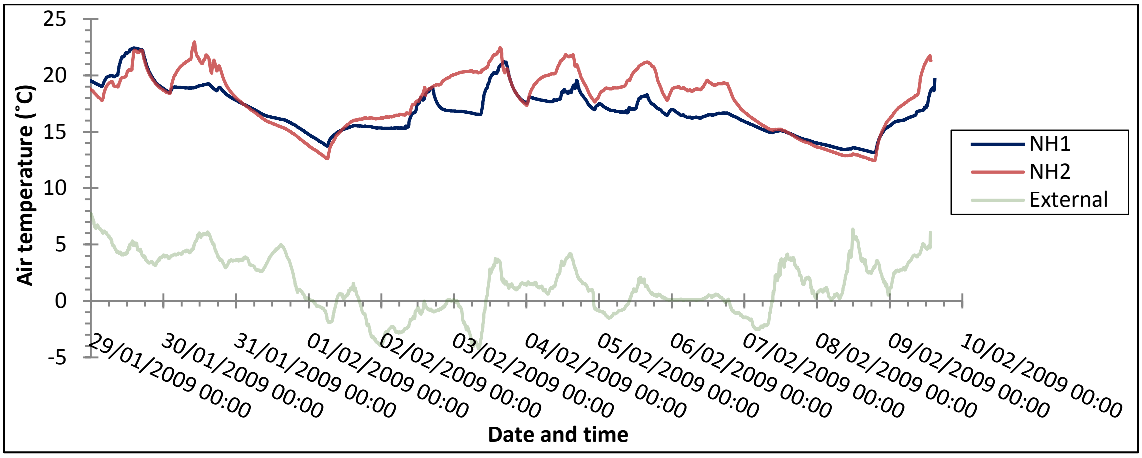


Figure 5.21: Diurnal winter air temperatures for the heavyweight single-occupancy offices.

During the weekends (e.g. 07/02/09 – 08/02/09) the temperatures do not follow the 'normal' diurnal pattern with distinctive peaks, suggesting that the occupants' operation of the spaces (including radiators being on) plays a significant role in the formation of the peaks. Over the weekends, the indoor air temperatures were almost constant and were reaching the minimum of the week.

Over the winter monitoring, NH6 had a problem with its IAQ, as its maximum CO_2 levels were higher than the suggested range (1000 – 1400ppm) for moderate air (BS EN 13779, 2007) (Table 5.11).

Table 5.11: Carbon dioxide levels for the heavyweight multi-occupancy offices.

Heavyweight		**Carbon dioxide level (ppm)**			**% of time CO_2 was >1500ppm (%)**
Monitoring period	**Orientation**	Av	Max	Min	
04/12/08 – 08/12/08	SH2	558	1199	395	0
	NH6	786	2167	375	33
09/02/09 – 19/02/09	SH2	857	2206	422	14
	NH6	1139	2834	357	37

The suggested maximum CO_2 levels were exceeded during the working hours by 33% over December and by 37% over February, suggesting that there is an insufficient number of air exchanges per hour within the room. Occupants in the north-facing multi-occupancy office were often complaining about feeling tired, sleepy and having headaches after being in the office for some time. The occupants were informed about the high levels of CO_2 in their offices and were advised to open their windows more often, as their symptoms were associated with poor indoor air quality. Consequently the occupants had taken the advice and were opening the windows more often and for longer periods, and their symptoms were eliminated, and the same was observed also in the summer monitoring. However this supports the findings of Raja *et al*. (2001) that if the outdoor air temperature is below 15°C, few occupants open their windows.

The south-facing office never exceeded the suggested maximum CO_2 concentration of 1400ppm in December (based on the outdoor CO_2 concentration and BS EN 13779), however during February, it exceeded it by 14%. February was very cold (Table 5.1), and hence the windows were not operated as frequently or for the same length of time as over the December period. This resulted in an increase in concentration of the CO_2 levels in the office. The number of occupants in the office was the same for both of the winter monitoring periods and hence this increase cannot be due to occupancy levels. The door of office SH2 is always open when the occupants are present, and hence it still has lower CO_2 levels despite more occupants being present, when compared to the CO_2 levels of office NH6 which has its door always closed.

5.1.4 Window and Door Operation

Other factors that contribute to the air temperature of internal spaces, apart from thermal mass and orientation, are the way the spaces are used by the occupants, i.e. the number of windows they are opening, the timings the windows are open and the state of the door. Opening the windows and/or the doors in the offices does not only affect the indoor air temperature, but also the CO_2 concentration. Some occupants open the windows from the morning time until night-time despite the weather outside (e.g. office occupant WL1) and others open the windows often over a span of a few minutes to cause disturbance in the indoor air temperature (e.g. office occupant WL4). In some cases it is therefore realistic to assume that windows are open for long enough to reach a steady state condition and hence it does not matter how much the window is open with respect to what temperature is reached indoors.

Depending on the orientation of offices, wind velocity will be different, and hence some offices experience a draught. For example, occupants of the north- and south-facing offices in the heavyweight building have complained about draughts when they open the window (that causes the papers in their office to move around, e.g. occupant of office NH4). None of the occupants of the lightweight spaces have complained about problems with draughts.

CIBSE (2006) suggests that for the ventilation to be effective in single-sided ventilation (all offices located in 4E), the length of the office should be less than or equal to 2 times the height of the office. For double-opening single-sided ventilation (all offices in 6E) the length of the office should be less than or equal to 2.5 times the height of the building. The offices that are prone to having insufficient ventilation are the multi-occupancy, SH2 and NH6. In order for the ventilation to be effective (as height is 3m) the length of the offices has to be less than or equal to 6m. This means that NH6 (external to internal wall: 4.3m) can have effective single-sided ventilation, but SH2 cannot (exceeds the suggested maximum of 6m). However, the door of NH6 is open when the occupants are present, hence it does not matter that the length of the room exceeds the suggested maximum, as there is a potential for cross-ventilation if the door and windows are open.

Looking at the data of multi-occupancy offices for the winter period (December and February), it appears that office SH2 always has its door open when occupants are present unlike office NH6 (Table 5.12). There is a very frequent door operation in office NH6 unlike for office SH2, where the door is left open, unless all the occupants leave for long periods of time. The reason for the occupants leaving the door shut for the office NH6 is that there is a busy corridor located directly behind the door and the occupants get distracted by people passing. Most occupants in NH6 have complained about the corridor, especially during the semester time. Office SH2 is located at the end of a corridor, and hence occupants do not have a problem with noise.

Table 5.12: Average window and door operations for the heavyweight multi-occupancy offices for winter.

Winter monitoring	Percentage of windows open when occupants are in the office					Correlation of indoor air temperature with state of window	Percentage of time door is open when occupants are in the office
	0	1	2	3	4		
SH2	100	0	0	0	0	None	100
NH6	99.9	0.1	0	0	0	None	0

<u>Note:</u> The percentage of windows and doors open when the occupant is in his office is an assumption based on the state of the windows and door when the occupants were filling in the questionnaires.

Office NH6 had only one of its windows operated once in February for two hours. Just before the opening of the window, the office had one of the second highest indoor air temperatures (21.9˚C) for that monitoring period. The south-facing office had all the windows shut, apart from three instances where the window was opened for two seconds. When the occupants were asked about their usage of the windows, all occupants who were not located near a window almost never used them. In fact, it was soon discovered (from the subjective data collection) that the occupants located away from the windows were not even aware of the number of windows open in their office.

As the indoor air temperature was higher than the outdoor air temperature (up to 20˚C difference for SH2 and 15˚C for NH6) (Figure 5.16), opening the windows would cause significant heat loss. However, there should be a trade-off that needs to be addressed between the amount of heat lost and the CO_2 levels which are exceeding the 1500ppm limit.

Over summer, the occupants of office SH2 continued to have their door continually open when present (Table 5.13). However, more windows (three; and only the bottom part) were operated during the very warm periods ($T_{max\ in}$ = 28˚C) by the occupants who had their desks next to the windows. The north-facing office had up to four windows open at one time, as well as their door. The academic year for the undergraduate students was over and hence the corridors were quiet.

Table 5.13: Average window and door operations for the multi-occupancy offices for summer.

Multi-occupancy offices Summer monitoring		Percentage of windows open when the occupants are in the office					Correlation of indoor air temperature with state of window	Percentage of time the door is open when occupants are in the office
		0	1	2	3	4		
Lightweight	SL5	10.3	27.6	13.8	20.7	27.6	Strong ($r = 0.743$, $p < 0.001$) ($r^2 = 0.552$, $p < 0.001$)	75.9
	NL1	16.7	3.7	79.6	N/A	N/A	Moderate ($r = 0.452$, $p < 0.001$) ($r^2 = 0.204$, $p = 0.001$)	44.4
Heavyweight	SH2	0	12.8	51.3	35.9	0	Moderate ($r = 0.677$, $p < 0.001$) ($r^2 = 0.458$, $p < 0.001$)	100
	NH6	0	47.6	47.6	1.9	2.9	Moderate ($r = 0.499$, $p < 0.001$) ($r^2 = 0.249$, $p < 0.001$)	15.5

During the same monitoring week, the occupants of the multi-occupancy south-facing lightweight offices (SL5) opened all four windows at a time, in an attempt to reduce heat discomfort. The north-facing office (NL1) has only two windows compared to the four of office SL5, despite being a much deeper office. Office SL5 had the door open 74% of the time when the occupants were present, enabling cross-ventilation, unlike the north-facing office, where the door was open 45% of the time. There were higher internal heat gains due to the larger number of occupants and electrical equipment in NL1, and overall there was less fresh air with fewer air exchanges causing CO_2 levels to exceed the suggested levels.

The lightweight offices have all available windows open unlike the heavyweight offices where more windows can be opened. Without further adaptive opportunities available, the lightweight offices had to use assisted ventilation. The lightweight offices had a fan operating during the warmest days which was used when the temperature exceeded 27˚C (on average). Once switched on, it was not switched off until the occupants left the room at the end of the working day. The heavyweight offices had no fans used even during the warmest days.

The operation of the windows of the single-occupancy offices varies depending on the occupant. The occupant of office EH1, for example, had one window open at all times independent of the external air temperature (Table 5.14).

Table 5.14: Average window and door operations for the single-occupancy offices for summer.

Single-occupancy offices Summer monitoring		Percentage of windows open when the occupants are in the office					Correlation of indoor air temperature with state of window	Percentage of time the door is open when the occupants are in the office
		0	1	2	3	4		
Lightweight	SL1	9.6	61.5	28.8	0	0	Moderate ($r = 0.462$, $p < 0.001$) ($r^2 = 0.214$, $p < 0.001$)	28.8
	EL1	27.3	72.7	0	0	0	Moderate ($r = 0.671$, $p < 0.001$) ($r^2 = 0.450$, $p < 0.001$)	87.9
	WL1	14.3	4.8	81.0	0	0	None ($r = 0.080$, $p < 0.001$) ($r^2 = 0.006$, $p < 0.001$)	71.4
Heavyweight	EH1	0	100	0	0	0	None	26.1
	NH2	0	100	0	0	0	None	94.6

The occupant of office EL1 was operating the window in accordance with the outdoor air temperature (Table 5.14). Both occupants never opened a second window in their office despite the high indoor temperatures (EH1: $T_{max\ in}$ = 27˚C, EL1: $T_{max\ in}$ = 38˚C), and never used a fan. Nevertheless, when the occupant of EL1 was in her office, the door was open 85% of the time, assisting in cross-ventilation, hence decreasing the indoor air temperature. In contrast, the occupant of EH1 had it open only 26% of the time that he was present. With only one window open and the door shut there was single-sided ventilation which is not as effective as cross-ventilation.

During the first phase of the summer monitoring period, where the outdoor air temperatures were high (up to 37°C), the occupant of NH2 had only one of the four possible windows open in his office and no assisted ventilation. The lightweight offices had both windows open almost constantly and a fan working in their office when the temperature was above 23˚C (SL1), or 26˚C (WL1), until they were leaving their office. The occupant of WL1, on the day when it was 32˚C, mentions that he was having cold drinks with ice in order to reduce heat discomfort.

The occupant of the office SL1 had her door shut 75% of the time when she was in her office, reducing the amount of cross-ventilation in her office. However, the operation of the doors and windows depends on the average change of state of the office doors of the south-facing lightweight offices with the average opening time being 28% (Table 5.15).

Table 5.15: Comparison of the window and door operation of different for the second part of the summer.

Thermal mass	Office	Percentage of time each window is open when the occupant is in the office				Percentage of time the door is open when the occupant is in the office
		1	2	3	4	
Lightweight	SL2	92	8	N/A	N/A	8
	SL3	46	18	N/A	N/A	63
	SL4	100	0	0	0	23
Heavyweight	SH1	100	0	0	0	100
	NH4	100	0	0	0	100

Most of the occupants in this section of the lightweight building have their door shut due to the noisy corridors. The occupant of office SL3 usually leaves his door open at 90˚ usually, whereas the occupant of office SH1 has his door open at a maximum angle of approximately 25˚C. The occupant of SH1 had his window open throughout the day (day-time and night-time), but the occupant of SL3 had it open only when present in his office. The occupant of NH4 had his window open when in his office (100% of the time) but did not leave his window open overnight. Leaving the window open over night-time (night-time ventilation), is considered beneficial (decreases indoor temperature) for office buildings in the summer (Kolokotroni and Aronis, 1999, Wang *et al.*, 2009). The effect of night ventilation is observed on offices SL3 and NH4 (SL3 is almost constantly 2˚C cooler than NH4, despite direct solar radiation for SL3 during day-time).

Comparing the operation of the windows and doors over the winter and autumn/spring periods (Table 5.16 – averaged for the monitored offices facing in the same direction), it can be observed that the operation of the windows over the various seasons for the same offices is significantly different ($t_{heavyweight}$ = -15.4, $p_{heavyweight}$ = 0.001; $t_{lightweight}$ = -9.83, $p_{lightweight}$ = 0.001). The correlation of the operation of the window with the season is moderate ($r_{heavyweight}$ = 0.231, $p_{heavyweight}$ < 0.050; $r_{lightweight}$ = 0.520 , $p_{lightweight}$ < 0.001).

Table 5.16: Annual operations of windows and doors for the offices of different thermal mass and orientation.

Single-occupancy offices			Percentage of windows open when occupants in the office					Correlation of indoor air temperature with state of window	Percentage of time door is open when occupants are in the office
Season	**Thermal Mass**	**Office**	0	1	2	3	4		
Winter	Lightweight	West (WL3 & WL4)	92.9	7.1	0	0	0	Moderate ($r = 0.557$, $p < 0.001$) ($r^2 = 0.311$, $p < 0.001$)	61.1
	Heavyweight	North (NH1 & NH2)	71.4	28.6	0	0	0	Moderate ($r = 0.501$, $p < 0.001$) ($r^2 = 0.251$, $p < 0.001$)	81.0

Table 5.16 continued.

Single-occupancy offices			Percentage of windows open when occupants in the office					Correlation of indoor air temperature with state of window	Percentage of time door is open when occupants are in the office
Season	**Thermal Mass**	**Office**	0	1	2	3	4		
Autumn & Spring	Lightweight	West (WL3 & WL4)	50.0	35.7	14.3	0	0	Moderate ($r = 0.325$, $p < 0.001$) ($r^2 = 0.106$, $p < 0.001$)	71.4
	Heavyweight	North (NH1 & NH2)	40.0	33.3	26.7	0	0	Moderate ($r = 0.529$, $p < 0.001$) ($r^2 = 0.279$, $p < 0.001$)	66.7

The occupants operate the windows similarly in autumn and spring, despite the orientation of the offices or the thermal mass. During winter, the heavyweight offices operate their windows more often (28.6 % open when in their office) than the lightweight offices (7.1 % open when in their office). Most of the occupants of the single-occupancy offices have their doors open when in their office independently of the time of day or year (Tables 5.14, 5.15 and 5.16).

5.1.5 Section Conclusion

Almost all monitored lightweight offices (multi- and single-occupancy), suffer from overheating during summer and partly through autumn. The extremely high temperatures (up to 38°C in some cases), affected the occupants, and they were forced to change their daily activities e.g. were not coming in to the offices. On average, the indoor air temperature during the occupied hours exceeded 25°C by 67 % during the first period of the summer monitoring which captured the mini heat-wave. Although no office was continually monitored throughout the year, if the assumption is made that during the rest of the summer (June – August) indoor temperatures were below 25°C (unlikely), then the building still has a problem with overheating when the building is free-run (10% of occupied hours is above 25°C).

Contrarily, the heavyweight offices exceed the suggested 25˚C by 6% (assuming that the temperatures are less than 25°C during the other summer weeks – which is a safe assumption when looking at the temperatures at the beginning of the summer monitoring). Although, according to CIBSE (2006), this building has a problem with overheating as indoor air temperatures are above 25°C for more than 5% of the occupied hours, maximum temperatures were never above 27°C, and hence it is not as much of a problem as for the lightweight offices.
Building parameters like thermal mass and orientation influence the indoor air temperatures reached in the offices. Single-occupancy offices located in the heavyweight building were overall cooler in summer (up to 10˚C) than identical offices located in the lightweight building. Over winter, the average indoor air temperatures of the offices lie within the comfortable range (19 – 24°C), irrespective of the thermal mass of the offices, with the heavyweight offices being cooler. Orientation has a more significant influence on the indoor air temperatures in the lightweight offices (up to 5°C difference – between east and west) than for the heavyweight offices (up to 2°C difference between north and south).

There is a strong correlation between the lightweight indoor air temperatures of offices of different occupancy levels. Although, for the heavyweight offices, the indoor air temperatures are similar for the offices of different occupancy levels, the single-occupancy ones show a greater amplitude in their indoor air temperatures. The greater variation is believed to be related to the heat exchanges occurring through the exposed roof of NH2.

Further, it was concluded that occupants operate their windows and doors differently, despite being exposed to the same environmental conditions. In turn, the operation of the windows and doors (causing cross-ventilation or single-sided ventilation) influence the indoor air temperatures and the CO_2 concentrations.

5.2 SUBJECTIVE DATA

Questionnaires were given to the occupants throughout the monitoring period to monitor the effect of the indoor thermal environment on the state of comfort. A total of 513 questionnaires were collected over the monitoring year. The first set of questionnaires given to the occupants had an extra section asking about the likeness of various environmental factors related to their offices, such as temperature, ventilation and noise level. The occupants were then asked to rate the personal importance of each factor on a seven point scale. Thereafter, the fingerprinting of each factor was calculated, which assisted in understanding the reasons for the way the occupants were operation their spaces, (details on the fingerprinting analysis can be found in Appendix 3).

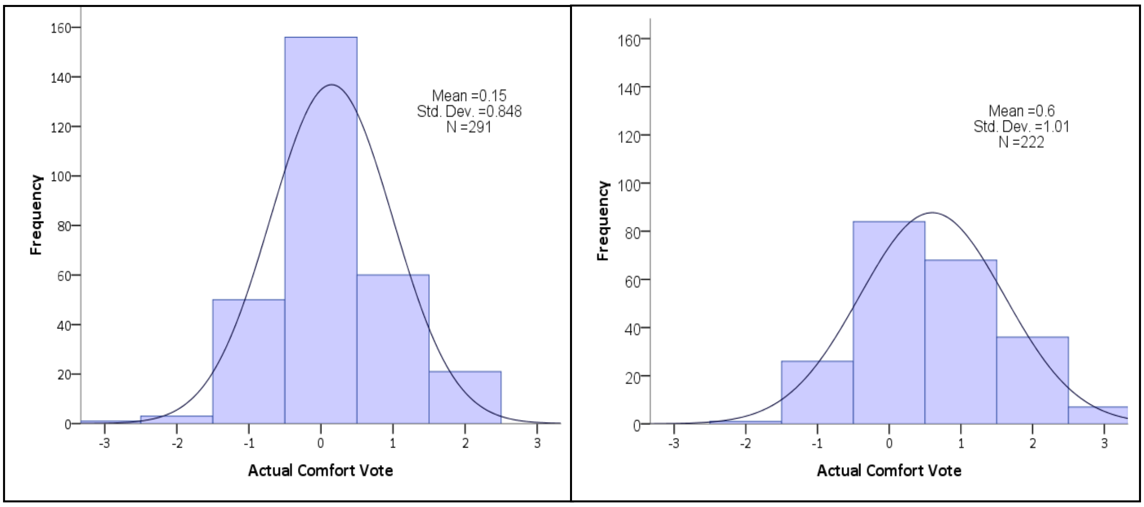
In the analysis of the results below, the terms thermal sensation and thermal comfort are interchangeable.

5.2.1 THERMAL COMFORT

Occupants can achieve comfort in their spaces by either adapting to the building's conditions or adapt the building to suit their preferences (Nicol, 2008). Although the occupants of the buildings studied have the same adaptive opportunities available to them, the data collected show that there are discrepancies in their actual thermal sensation votes (CV ranging from -3 (cold) to 3 (hot)). Office orientation and thermal mass of the buildings appear to be two of the reasons that cause different indoor air temperatures and hence influence their comfort vote.

5.2.1.1 Building's Thermal Mass

Analyzing all comfort votes collected (over the different seasons and for the different occupancy levels) indicates that there are significant differences in the thermal comfort of the occupants of the lightweight and heavyweight offices ($F_{(1,511)} = 30.2$, $p < 0.001$). The majority of the actual thermal sensation votes for the heavyweight buildings are distributed around the slightly cool to slightly warm (CV: -1 to 1), whereas for the lightweight building they are between neutral and warm (CV: 0 to 2) (Figure 5.22). There are more occupants feeling neutral in the heavyweight building than in the lightweight building (difference approximately 15%). Overall, occupants located in 4E are warmer than the offices located in 6E (heavyweight: $CV_{mean} = 0.15$, lightweight: $CV_{mean} = 0.5$).



Heavyweight offices Lightweight offices

Figure 5.22: Histograms showing the actual thermal comfort vote of the occupants, which ranges from -3 (cold) to 3 (hot).

Note: Data presented are from all the seasons (summer, spring / autumn and winter, and for all offices; single- and multi-occupancy).

There is a negative correlation between the preferred and actual thermal comfort votes for the single-occupancy offices, suggesting that the warmer the occupants feel the cooler their preferred vote and vice versa (Table 5.17). Nevertheless, the preferred comfort vote does not always reflect the vote that will bring the occupant in the state of thermal neutrality. Some occupants are comfortable with their thermal environment if they are warmer or cooler than the neutral state. Over summer, most occupants of the single-occupancy offices prefer to feel neutral or to be on the slightly cooler side of the scale, and for the winter season some occupants prefer to be on the warmer side of the scale.

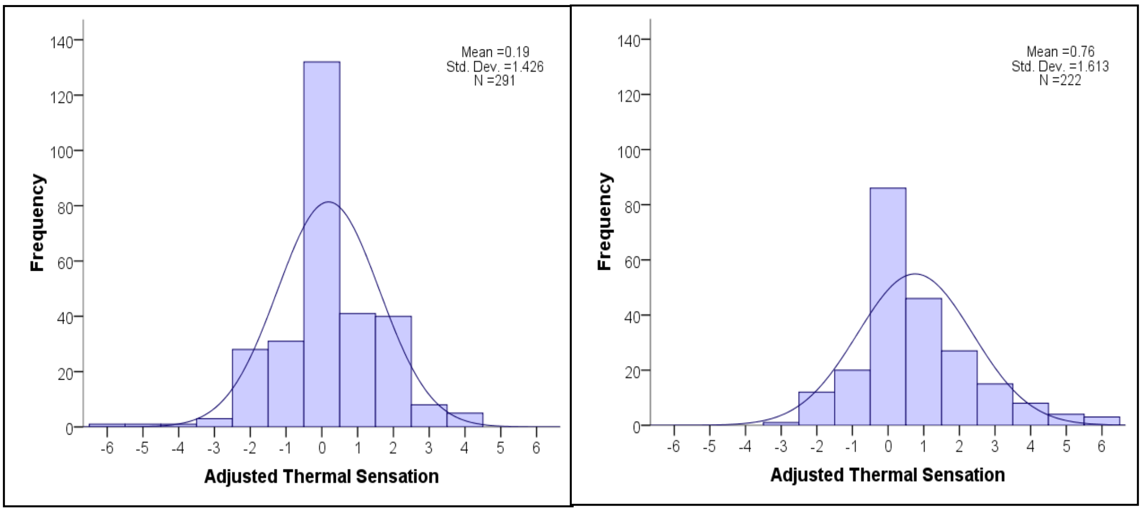
Consequently it was decided to take into account the preferred comfort vote of the occupants when looking at their actual thermal comfort votes (i.e. adjusted thermal sensation of the occupants[vii]). Combining the two votes in the general analysis (all data collected despite season, occupancy or office orientation) suggests that the occupants of the lightweight offices do not only feel warmer but it is not what they would prefer (Figure 5.23).

[vii] The '*adjusted thermal sensation*' (ATS) is calculated by subtracting the desired sensation of the subject from his/her actual sensation. It shows by how much the thermal sensation of a subject is different from his preferred sensation; i.e. ATS = 0, the subject is feeling as desired, ATS > 0, the subject feels warmer than desired, ATS < 0 the subject is feeling colder than he/she prefers. It is based on a study which analyzed the desired thermal sensation of 868 occupants based in university lectures and dwellings, and the findings suggested that when the ASHRAE scale is used the thermal sensation votes have to be adjusted. (Humphreys and Hancock, 2007).

Table 5.17: Relationship between actual and preferred thermal comfort vote of the occupants of the single-occupancy offices.

Season	Thermal mass	Orientation	Correlation between actual comfort vote and preferred comfort vote
Summer	Lightweight	West-facing	Strong r = -0.780, p = 0.001
		East-facing	Insignificant r = -0.062, p = 0.733
		South-facing	Moderate r = -0.404, p = 0.003
	Heavyweight	North-facing	Strong r = -0.722, p = 0.001
		East-facing	Strong r = -1.000, p = 0.001
		South-facing	Strong r = -1.000, p = 0.001
Autumn/Spring	Lightweight	West-facing	Insignificant r = -0.434, p = 0.106
	Heavyweight	North-facing	Moderate r = -0.676, p = 0.001
Winter	Lightweight	West-facing	Moderate r = -0.525, p = 0.025
	Heavyweight	North-facing	Moderate r = -0.467, p = 0.033

The distribution curve of adjusted thermal sensation vote of the heavyweight offices, is more evenly distributed about zero, whereas for the lightweight offices it is shifted to the positive scale (Figure 5.23). Consequently, it can be concluded with confidence that the majority occupants of the lightweight offices are uncomfortably warm / hot (ATS up to 6). The occupants of the heavyweight offices are equally uncomfortably warm and cool, but the majority are feeling just right (~45%).



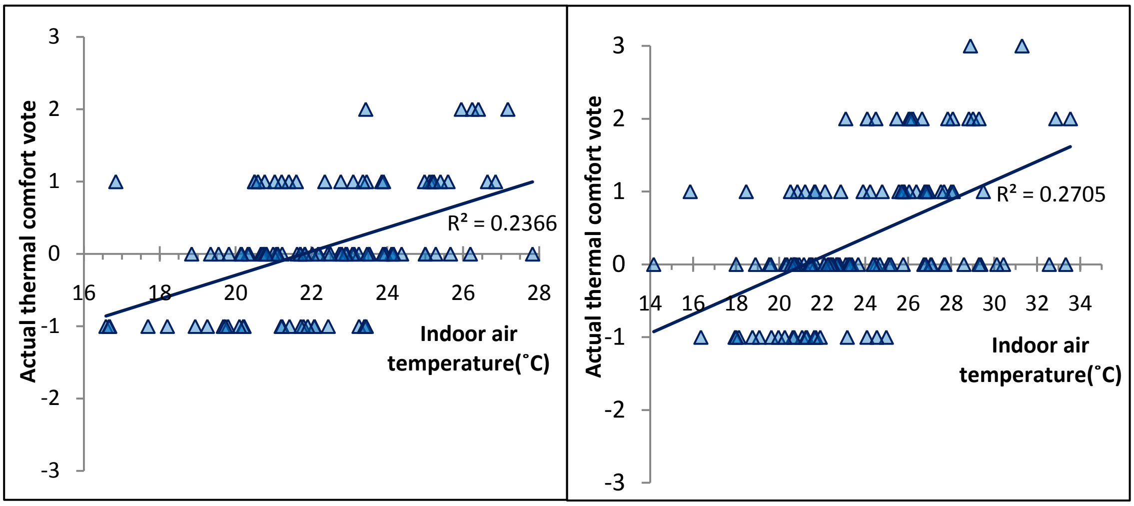
Heavyweight offices

Lightweight offices

Figure 5.23: Adjusted thermal sensation of the occupants located in buildings of different thermal mass.

Overall there is moderate correlation between the actual thermal comfort vote of single-occupancy offices and their corresponding indoor air temperatures in both buildings ($r_{heavyweight}$ = 0.486, $r_{lightweight}$ = 0.520) (Figure 5.24). This implies that the same temperatures are perceived the same by the occupants regardless of which building they are located in. Under the same temperature, the occupants of the single-occupancy offices have almost the same correlation between adjusted thermal sensation and their indoor air temperature ($r_{heavyweight}$ = 0.494, $r_{lightweight}$ = 0.502). Discrepancies in the adjusted thermal sensations of the occupants between the two buildings is largely influenced by the higher indoor air temperatures of the lightweight offices (Figure 5.23).

From Figure 5.24, it appears that the occupants of the two single-occupancy offices studied are comfortable (-1 ≤ CV ≤ 1) within a wider range of temperatures (heavyweight: 16 – 27°C; lightweight: 14 – 29°C) than suggested by the Carbon Trust (2007).



Heavyweight single-occupancy offices

Lightweight single-occupancy offices

Figure 5.24: Relationship between indoor air temperature and actual thermal comfort for the single-occupancy offices.

The correlation between indoor and outdoor air temperatures with the occupants actual thermal comfort vote varies depending on the season (Table 5.18).

Table 5.18: Correlation of indoor and outdoor air temperatures with the actual thermal comfort vote of the occupants of the single-occupancy offices.

Season	Thermal mass	Orientation	Correlation between actual comfort vote and indoor air temperature	Correlation between actual comfort vote and outdoor air temperature
Summer	Lightweight	West-facing	Strong r = 0.845, p < 0.001	Strong r = 0.849, p < 0.001
		East-facing	Moderate r = 0.596, p = 0.006	Insignificant r = 0.275, p = 0.128
		South-facing	Moderate r = 0.620, p < 0.001	Moderate r = 0.483, p = 0.001
	Heavyweight	North-facing	Moderate r = 0.454, p = 0.005	Moderate r = 0.376, p = 0.024
		East-facing	Strong r = 0.850, p < 0.001	Strong r = 0.768, p < 0.001
		South-facing	Insignificant r = 0.046, p = 0.892	Insignificant r = 0.268, p = 0.425

Table 5.18 continued.

Season	Thermal mass	Orientation	Correlation between actual comfort vote and indoor air temperature	Correlation between actual comfort vote and outdoor air temperature
Autumn / Spring	Lightweight	West-facing	Moderate r = 0.510, p = 0.052	Insignificant r = 0.214, p = 0.463
	Heavyweight	North-facing	Insignificant r = 0.308, p = 0.186	Insignificant r = 0.004, p = 0.986
Winter	Lightweight	West-facing	Insignificant r = 0.251, p = 0.315	Insignificant r = 0.463, p = 0.053
	Heavyweight	North-facing	Moderate r = 0.523, p = 0.018	Insignificant r = 0.398, p = 0.082

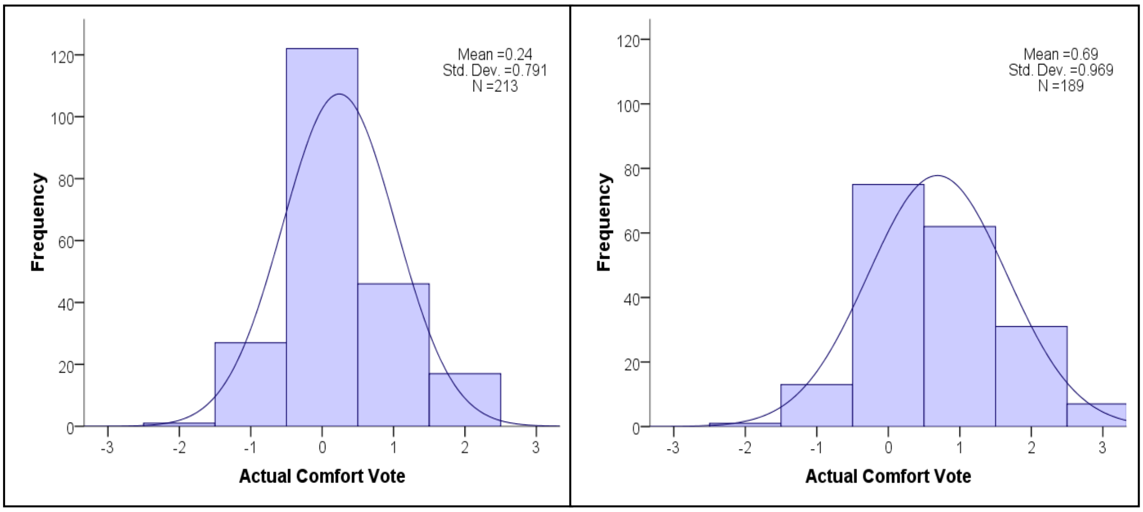
As expected, the comfort vote in most single-occupancy offices (Table 5.18) and multi-occupancy offices (Table 5.19), despite orientation or thermal mass, seems to be influenced more by indoor air temperature than by the outdoor air temperature. Over summer, when the building is in free-running mode, and the indoor temperature is highly correlated with the outdoor temperatures (Section 5.1), there is a stronger correlation between the outdoor air temperature and the comfort votes by the occupants. For example, the lightweight west-facing offices have a correlation with the outdoor air of 0.849 in the summer (free-ventilated), 0.463 in winter and 0.214 in mid-seasons (spring and autumn) (mechanically heated).

Table 5.19: Correlation of indoor and outdoor air temperatures with the actual thermal comfort vote of the occupants of the multi-occupancy offices.

Season	Thermal mass	Orientation	Correlation between actual comfort vote and indoor air temperature	Correlation between actual comfort vote and outdoor air temperature
Summer	Lightweight	North-facing	Moderate r = 0.696, $p < 0.001$	Moderate r = 0.597, $p < 0.001$
		South-facing	Strong r = 0.757, $p < 0.001$	Moderate r = 0.588, p = 0.001
	Heavyweight	North-facing	Moderate r = 0.528, $p < 0.001$	Moderate r = 0.490, $p < 0.001$
		South-facing	Insignificant r = 0.281, p = 0.083	Moderate r = 0.387, p = 0.018
Winter	Heavyweight	North-facing	Insignificant r = 0.403, p = 0.109	Insignificant r = -0.067, p = 0.800
		South-facing	Insignificant r = 0.476, p = 0.053	Insignificant r = -0.083, p = 0.743

As was concluded in Section 5.1, lightweight offices were warmer than heavyweight offices over summer, and as expected it has influenced the thermal sensation of the occupants. Even though most of the occupants were using fans in the lightweight offices, the assisted ventilation they used did not assist in the way they wished to feel. The actual comfort votes collected over summer (Figure 5.25) suggest that the occupants of the heavyweight offices never felt more than warm (CV = 2), unlike the occupants of the lightweight offices that some felt warm and others even hot (CV = 3) (5%). This supports the findings of the overall thermal comfort votes (data from all seasons) (Figure 5.22).

Once again, there are discrepancies in the adjusted thermal sensation votes between the occupants of the lightweight and heavyweight offices over summer ($F_{(1,400)} = 14.4$, $p < 0.001$), and the mid-seasons ($F_{(1,35)} = 10.6$, $p = 0.003$), but not over winter ($F_{(1,72)} = 2.10$, $p = 0.151$). Perhaps the reasons could be that over the winter period the auxiliary heating was on, and many occupants were using their own personal portable heaters to maintain comfort, hence the occupants were always feeling as they wished.



Heavyweight offices Lightweight offices

Figure 5.25: Histograms showing the actual thermal comfort of the occupants for the summer monitoring of all offices.

A comparison of the offices facing in the same direction and monitored at the same time, but located in the two different buildings, cannot be performed for the single-occupancy offices, apart from for the east-facing ones. Although based on a very small sample, performing a Mann-Whitney U test[viii] on the average actual thermal comfort vote of the east-facing single-occupancy lightweight office ($M = 0.33$, SD = 0.78) and heavyweight office ($M = 0.39$, SD = 0.99) showed that that there is no significant difference ($z = -0.39$, $p = 0.697$) between the two. This suggests that east-facing lightweight office occupants are tolerant of the much higher temperatures. Comparing the comfort vote of the two occupants for the same indoor air temperatures (e.g. range of 25 – 27°C), it was observed that the comfort vote of the occupant of EH1 was slightly warm to warm (CV: 1 to 2), whereas for the occupant of office EL1 was neutral (CV = 0). Although based on a small sample, this finding contradicts the conclusion of Karjalainen (2007) that females are more dissatisfied and tend to feel uncomfortable more often with their indoor air temperature than males, as it seems that female occupants prefer warmer conditions.

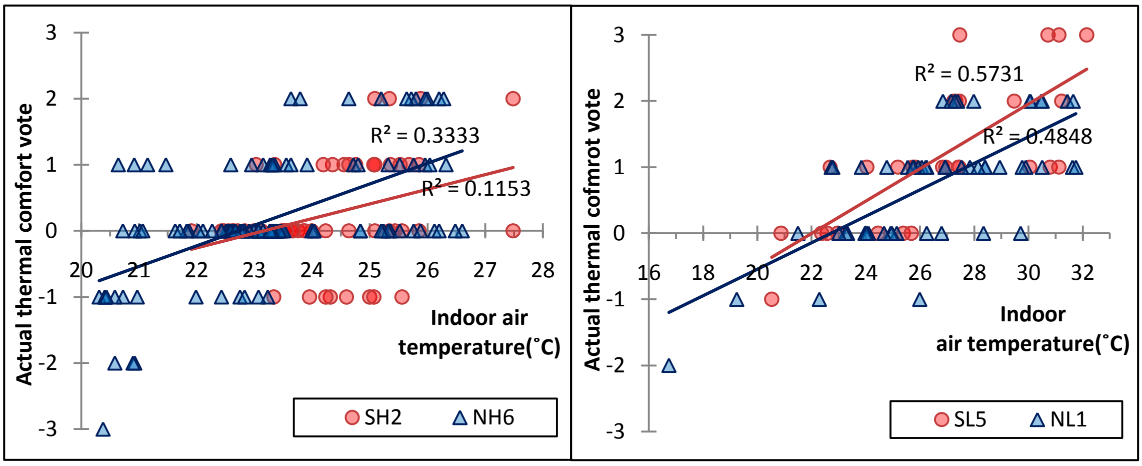
Unsurprisingly there is a significant difference in the thermal comfort vote of the occupants of the multi-occupancy offices in the two different buildings over summer ($M_{heavyweight} = 0.28$, $SD_{heavyweight} = 0.78$, $M_{lightweight} = 0.89$, $SD_{lightweight} = 0.98$, $z = -5.19$, $p < 0.001$). The data from the multi-occupancy offices suggests that there are significant differences in the comfort votes over summer for the south- and north-facing offices of different thermal mass ($M_{south\ lightweight} = 1.14$, $M_{south\ heavyweight} = 0.21$, $z = -3.81$, $p < 0.001$; $M_{north\ lightweight} = 0.76$,

[viii] Mann-Whitney U test is a non-parametric t-test for independent samples. One of the conditions to use this non-parametric test is that the data is ordinal. If the sample number is bigger than 20 (N > 20), then the *z* score is used instead of the U score as the normal distribution is approximated for U for samples over 20.

M_{north} heavyweight = 0.31, z = -3.59, p < 0.001). The indoor air temperatures in the heavyweight offices were lower than the temperatures in the lightweight offices at the corresponding times (Section 5.1).

5.2.1.2 Office Orientation

It is acknowledged that the data used for this section of the analysis is based on a small sample. Ideally the study should be performed on a larger scale to confirm the findings. The effect of indoor air temperature on the comfort vote for the lightweight multi-occupancy offices is similar for both the north- and south-facing offices (within 10% difference). However, for the heavyweight multi-occupancy north- and south-facing offices there is a higher difference (20% difference) than for the lightweight ones (Figure 5.26). Consequently, it is expected that there is an insignificant difference in the comfort votes of the occupants of the north- and south multi-occupancy lightweight offices (M_{south} = 1.14, SD_{south} = 1.06, M_{north} = 0.76, SD_{north} = 0.91, z = -1.319, p = 0.187) and similarly for the heavyweight offices (M_{south} = 0.21, SD_{south} = 0.73, M_{north} = 0.31, SD_{north} = 0.79, z = -0.616, p = 0.538).

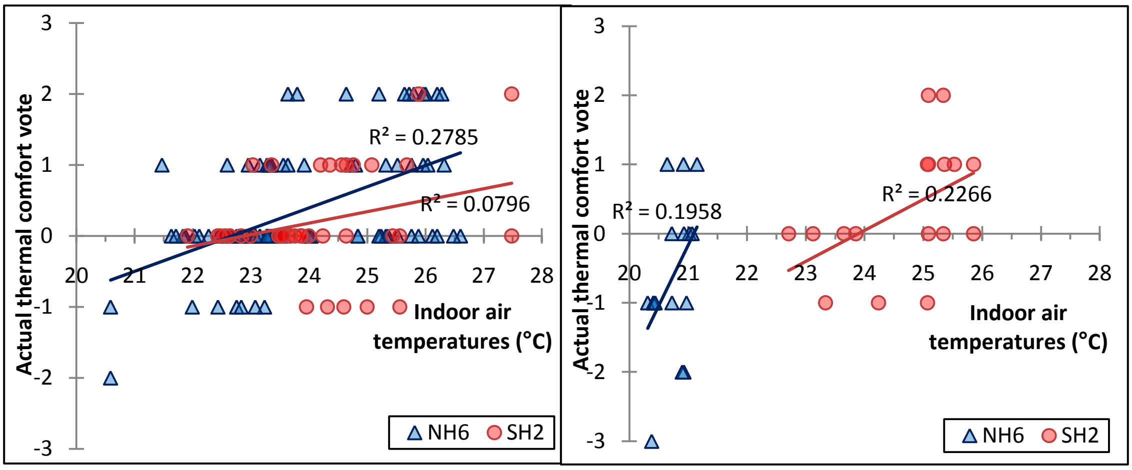


Heavyweight offices   Lightweight offices

Figure 5.26: Relationship of indoor air temperature and actual thermal comfort for the multi-occupancy offices.

Looking at the data of the heavyweight multi-occupancy offices over different seasons, a significant difference is observed in the comfort votes of the occupants of the north- and south-facing offices for the winter period (z = -2.540, p = 0.014) but not for the summer (z = -0.616, p = 0.538) (Figure 5.27). This difference is expected as the indoor air temperature of the south-facing office over the summer was on average 1˚C warmer than the north-facing office but over the winter the difference increased to 4˚C (Tables 5.4 and 5.9).

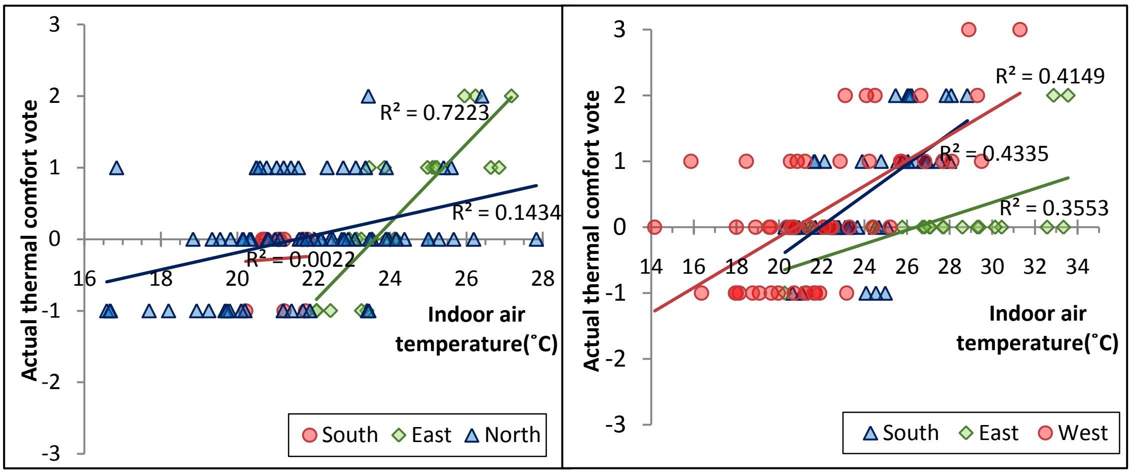
For the south-facing offices, the difference between the winter and summer actual comfort votes (M_{winter} = 0.28, M_{summer} = 0.35, z = -0.22, p = 0.807) is smaller (and insignificant) than the difference for the north-facing offices (M_{winter} = -0.71, M_{summer} = 0.31, z = -3.93, p = 0.001). This could be attributed to the similar temperatures over winter and summer for the south-facing offices (average difference 1°C), unlike for the north-facing, where over summer it is warmer than in winter (average 4.5°C).



Summer Winter

Figure 5.27: Comparing the actual thermal comfort vote with the indoor air temperatures for the heavyweight multi-occupancy offices.

When considering the extent of influence of the indoor air temperature on the thermal comfort vote of the occupants of the heavyweight offices, the data suggests that there is a strong correlation for the east-facing office but not the north- or south-facing offices. The results for the south-facing offices might have been different if the study was carried on for longer (different seasons), or if there were many more offices. As it was mentioned previously, there was only one single-occupancy south-facing office in this building, and the occupant was not particularly willing to participate. The actual thermal comfort vote of the occupants is moderately influenced by the variance in the indoor air temperature for all the single-occupancy lightweight offices (Figure 5.28).

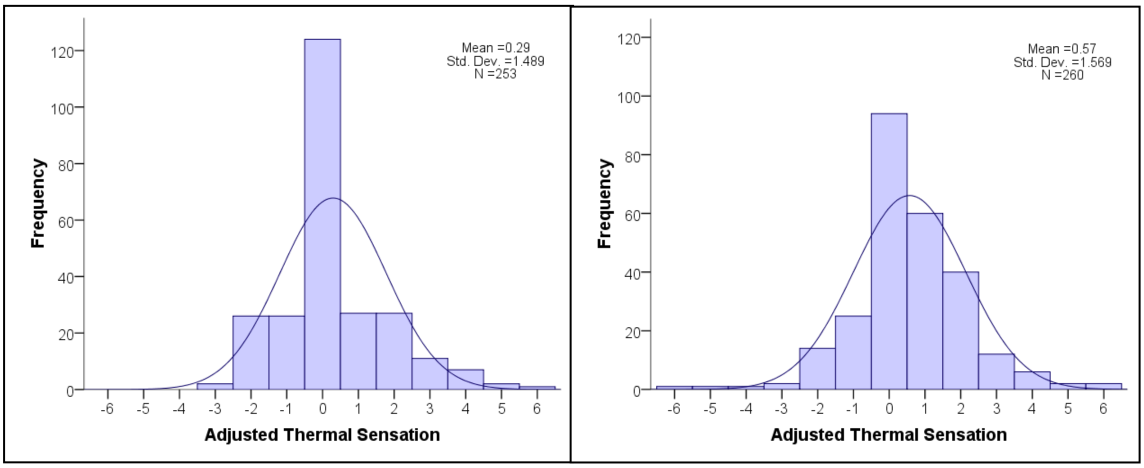


Heavyweight offices Lightweight offices

Figure 5.28: Relationship of indoor air temperature and actual thermal comfort for heavyweight single-occupancy offices.

5.2.1.3 Occupancy Levels

When comparing the single-occupancy and multi-occupancy thermal sensation data collected, regardless of the location of the offices (building and orientation), there is a significant difference in their actual thermal comfort votes (z = -2.04, p = 0.041) and their adjusted thermal sensation votes (z = -3.00, p = 0.003) (Figure 5.29). This suggests that the higher the level of control the more comfortable the occupants are (i.e. occupants of single-occupancy offices are more comfortable than the occupants of multi-occupancy offices).



Single-occupancy offices

Multi-occupancy offices

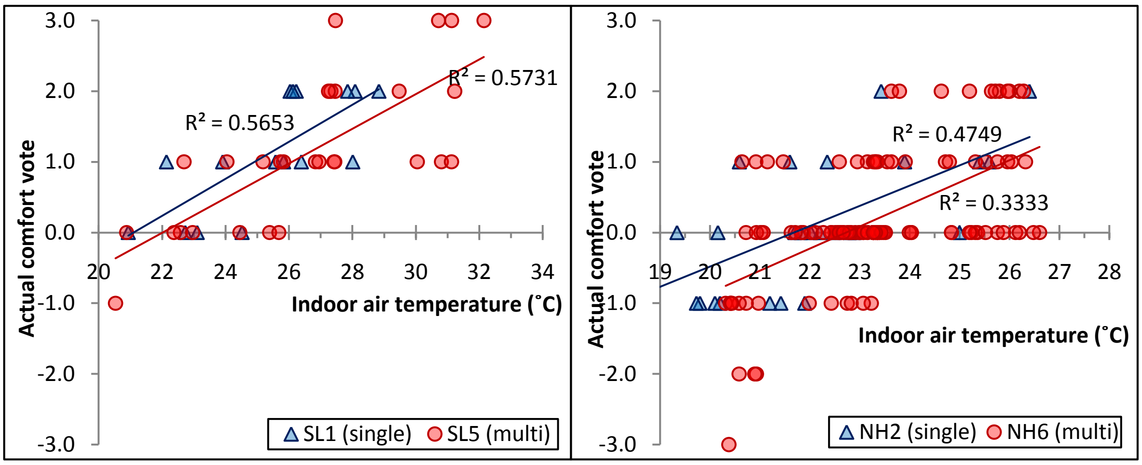
Figure 5.29: Adjusted thermal sensation of the occupants of different occupancy levels.

However, when comparing the thermal comfort votes for offices (single- versus multi-occupancy) in the same buildings, although there is a significant difference in their actual and adjusted thermal sensation votes for the lightweight offices (CV: $z = -3.64$, $p < 0.001$; ATS: $z = -4.58$, $p < 0.001$, that is not the case for the heavyweight offices (CV: $z = -1.15$, $p = 0.251$; ATS: $z = -1.19$, $p = 0.234$)) (Table 5.20).

Table 5.20: Comparing the thermal comfort votes of the occupants located in single- and multi-occupancy offices of different thermal mass.

Season	Thermal mass	Occupancy	Mean actual thermal comfort vote	Mean adjusted thermal sensation vote
Overall	Heavyweight	Single	0.09	0.12
		Multi	0.19	0.23
	Significantly difference		No $z = -1.15$, $p = 0.251$	No $z = -1.19$, $p = 0.234$
	Lightweight	Single	0.42	0.43
		Multi	0.89	1.30
	Significantly difference		Yes $z = -3.64$, $p < 0.001$	Yes $z = -4.68$, $p < 0.001$
Summer	Heavyweight	Single	0.15	0.24
		Multi	0.28	0.39
	Significantly difference		No $z = -1.02$, $p = 0.309$	No $z = -0.937$, $p = 0.349$
	Lightweight	Single	0.53	0.58
		Multi	0.89	1.30
	Significantly difference		Yes $z = -2.96$, $p = 0.003$	Yes $z = -4.08$, $p < 0.001$

Correlating the thermal comfort votes with the indoor air temperature for offices of the same orientation (and thermal mass) but different occupancy levels, it can be seen that they have almost the same moderate correlation (Figure 5.30). It was expected that occupants of the single-occupancy offices would be more comfortable with higher indoor air temperatures than the occupants of the multi-occupancy offices (Brager *et al.*, 2004), due to having more control over their spaces. Perhaps the occupants of the multi-occupancy offices were perceiving the same amount of control as the occupants of the single-occupancy offices, as the offices were not occupied by large groups (Leaman and Bordass, 1999b) and not by more than seven people at any given time, as was suggested by Doggart (2006).



Lightweight offices Heavyweight offices

Figure 5.30: The relationship between actual comfort vote and the indoor air temperature for offices of different occupancy levels.

5.2.1.4 Impact of Building Properties on Thermal Comfort

Multivariate Analysis of Variance (MANOVA) was performed on the different building properties considered in this thesis (thermal mass, office orientation and occupancy levels), to check their effect on the indoor air temperatures reached in the offices and the actual and adjusted thermal sensation of the occupants (Table 5.21).

Table 5.21: Relationship between the clo-value and the indoor and outdoor air temperature.

Building property	Dependant variables	Effect of building variables on dependant variables.	Rank of importance[ix]
Thermal Mass	Actual thermal sensation	Significant (F(1,486) = 13.466, *p* < 0.001)	2
	Adjusted thermal sensation	Significant (F(1,486) = 7.988, *p* = 0.005)	
	Indoor temperature	Significant (F(1,486) = 87.031, *p* < 0.001)	
Office Orientation	Actual thermal sensation	Insignificant (F(3,486) = 0.694, *p* = 0.556)	3
	Adjusted thermal sensation	Insignificant (F(3,486) = 2.001, *p* = 0.113)	
	Indoor temperature	Significant (F(3,486) = 31.867, *p* < 0.001)	
Occupancy Level	Actual thermal sensation	Significant (F(1,486) = 12.898, *p* < 0.001)	1
	Adjusted thermal sensation	Significant (F(1,486) = 17.076, *p* < 0.001)	
	Indoor temperature	Significant (F(1,486) = 54.110, *p* < 0.001)	

[ix] Rank of importance is based on ordering the average *p*-value in increasing order.

The thermal capacity of the building and the occupancy level of the offices has a significant effect on all the variables tested (adjusted thermal sensation, actual thermal sensation and indoor air temperature). The orientation of the offices affects the indoor air temperature of the offices significantly but not the actual or adjusted thermal sensation of the occupants. The indoor air temperature reached in the offices is mostly affected by the thermal mass of the building followed by the occupancy level of the offices and lastly by the orientation of the offices (based on the F-value; higher F-value means a stronger relationship).

The adjusted thermal sensation of the occupants is mostly affected by the occupancy level, followed by the thermal mass and then the office orientation (based on the F-values). This finding suggests that occupants of single-occupancy offices, which have more control over their spaces, are more comfortable than the occupants of multi-occupancy levels, supporting the findings of Brager, *et al.* (2004). The actual thermal comfort of the occupants is mostly affected by thermal mass, followed by the occupancy level and lastly by the office orientation.

5.2.3 Clothing Insulation

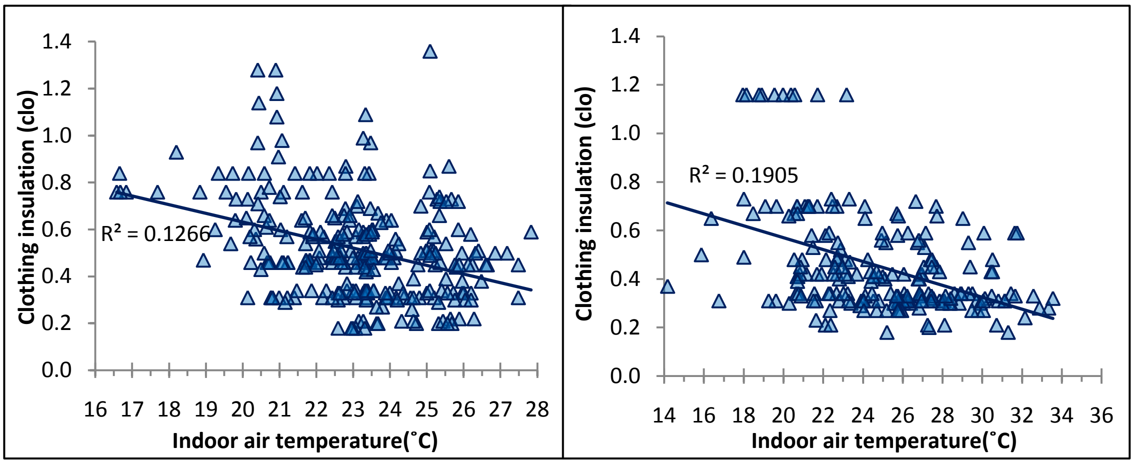
Clothing is one of the factors that affect the thermal comfort of the occupants (Humphreys, 1976). The level of clothing insulation used by the occupants is more correlated to the outdoor air temperature than the indoor air temperature (Table 5.22).

Table 5.22: Relationship between the clo-value and the indoor and outdoor air temperature.

Occupancy	Thermal Mass	Linear regression between indoor air temperature and clothing insulation value (R^2)	Linear regression for outdoor air temperature and clothing insulation value (R^2)
Single-occupancy	Lightweight	0.248	0.555
	Heavyweight	0.091	0.515
Multi-occupancy	Lightweight	0.213	0.324
	Heavyweight	0.135	0.401

Through informal interviews some occupants have mentioned that they do not like to change their clothes throughout the day despite not being comfortable with their indoor environment. This explains the higher correlation between the outdoor air temperature and the clothing insulation than with the indoor air temperature, which supports the conclusions of Barlow *et al*. (2007). People get dressed for the day, hence as described by De Carli *et al*. (2007) the clothing insulation value is more significantly correlated to the outdoor air temperature, than with the temperature at any specific time of day.

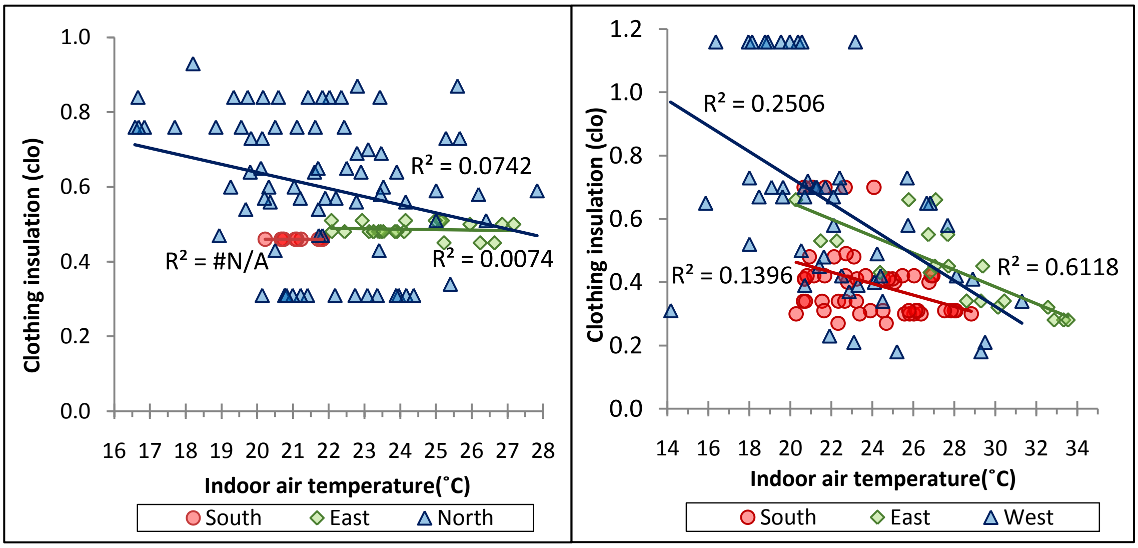
The clothing insulation of the occupants of the two buildings is on average very similar. The occupants of the lightweight single-occupancy offices are usually just a little more lightly dressed than the occupants of the heavyweight offices for temperatures over 21°C, and slightly more heavily dressed for temperatures below 21°C (Figure 5.31).



Heavyweight offices Lightweight offices

Figure 5.31: Comparing the clothing insulation with the indoor air temperatures for the lightweight and the heavyweight single-occupancy offices.

Occupants of the heavyweight building, despite the orientation of their offices, tend to keep the same dress code despite the external temperatures (Figure 5.32). There is a higher correlation between the clothing insulation and the indoor air temperature for the occupants of the lightweight building (Figure 5.32). For the east-facing offices the subject was female, and the change in the indoor air temperature is responsible for 61% of the change in her clothing, when compared to the 25% for the mixed sample for the west-facing offices. Occupants of the lightweight offices in some cases came in to their office with shorts when it was warm (approximately 29°C).



Heavyweight offices Lightweight offices

Figure 5.32: Clothing insulation for the lightweight offices of different orientation.

The heavyweight offices have a slightly weaker correlation between the indoor air temperature and the clothing insulation of the occupants than the lightweight offices (Figure 5.33). That could be related to the indoor air temperatures of the heavyweight offices drifting less away from the suggested comfort range (19 – 24°C), unlike the lightweight offices, hence there is a smaller range to correlate.

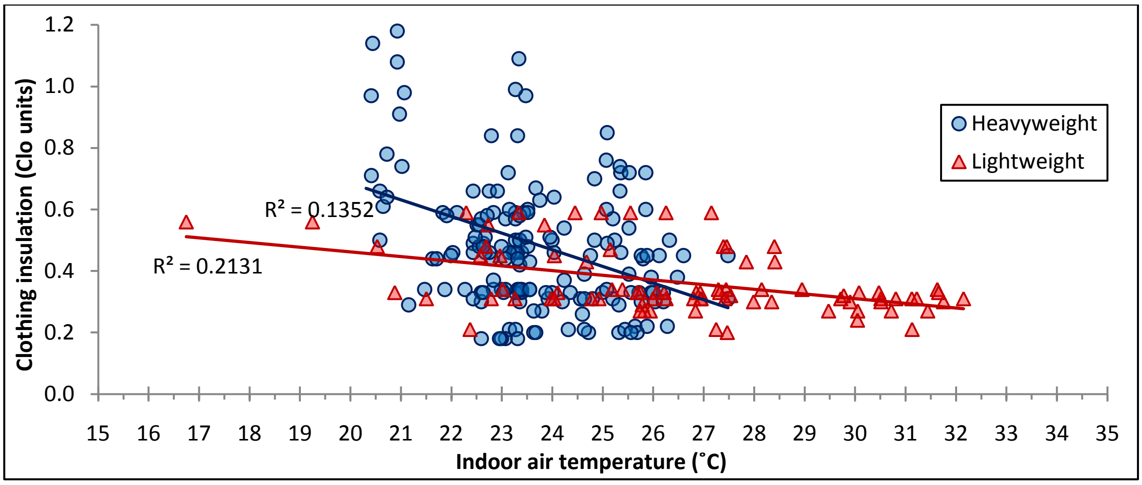
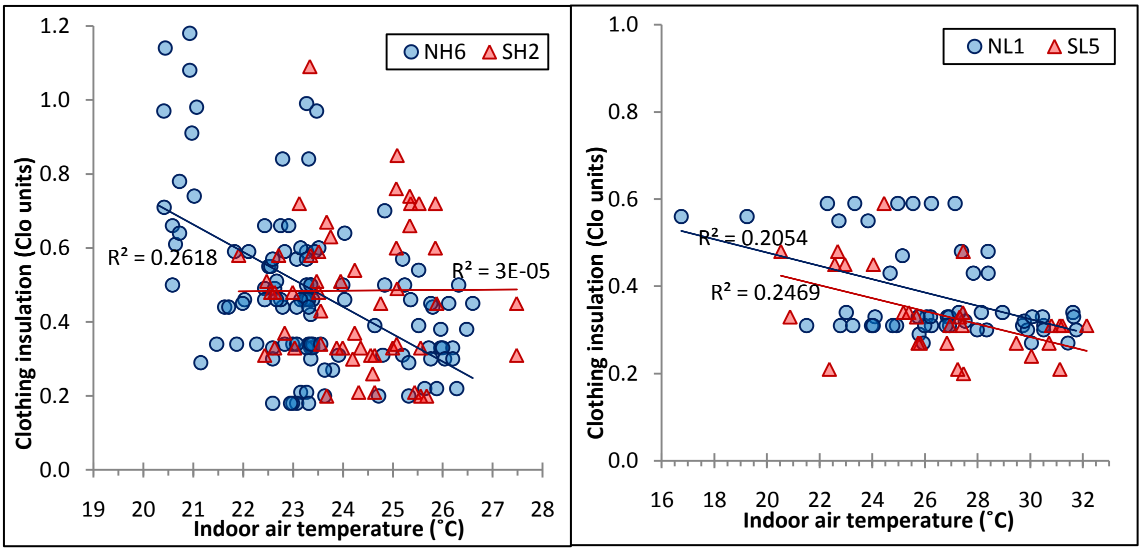


Figure 5.33: Comparing the clothing insulation with the indoor air temperatures for the lightweight and the heavyweight multi-occupancy offices over different seasons.

Looking at the multi-occupancy data in terms of office orientation, there is no correlation between the indoor air temperature and the clothing insulation for office SH2. Office NH6 has a moderate correlation between the indoor air temperature and the clothing insulation of the occupants ($r = 0.511$, $p < 0.001$) (Figure 5.34). Office SL5 has a marginally lower average indoor air temperature during the working hours than the north-facing office (T_{diff} = 0.3°C) (Table 5.4), yet the occupants of office SL5 are usually more lightly dressed than the occupants of office NL1 (Figure 5.34). The south-facing occupants still feel uncomfortably warmer than the occupants of NL1 (CV higher by 0.38).



Heavyweight offices

Lightweight offices

Figure 5.34: Relationship of clothing insulation with indoor air temperatures for the multi-occupancy offices.

In general, the occupants (single- and multi-occupancy) of the heavyweight building are dressed more heavily than the occupants of the lightweight offices over summer ($clo_{heavyweight}$ = 0.44, $clo_{lightweight}$ = 0.40) ($F_{(1,400)} = 8.74$, $p = 0.003$). Over winter the occupants in the heavyweight building are dressed more lightly than the occupants of the lightweight building ($clo_{heavyweight}$ = 0.81, $clo_{lightweight}$ = 0.96) ($F_{(1,67)} = 6.08$, $p = 0.016$).

Looking only at the data of the heavyweight multi-occupancy offices, there is a difference in the clothing insulation of the occupants between winter and summer for both the north- and south-facing offices (Figure 5.35).

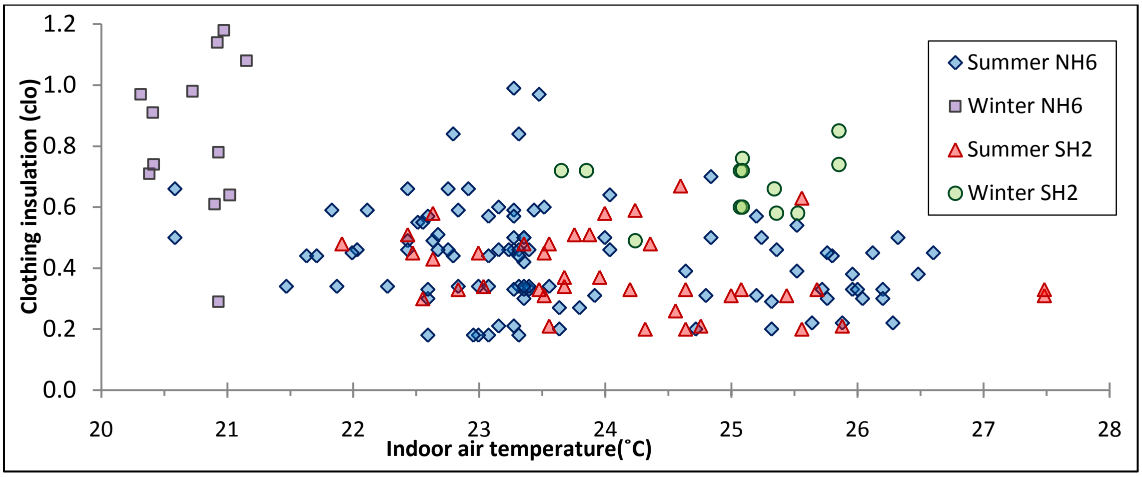
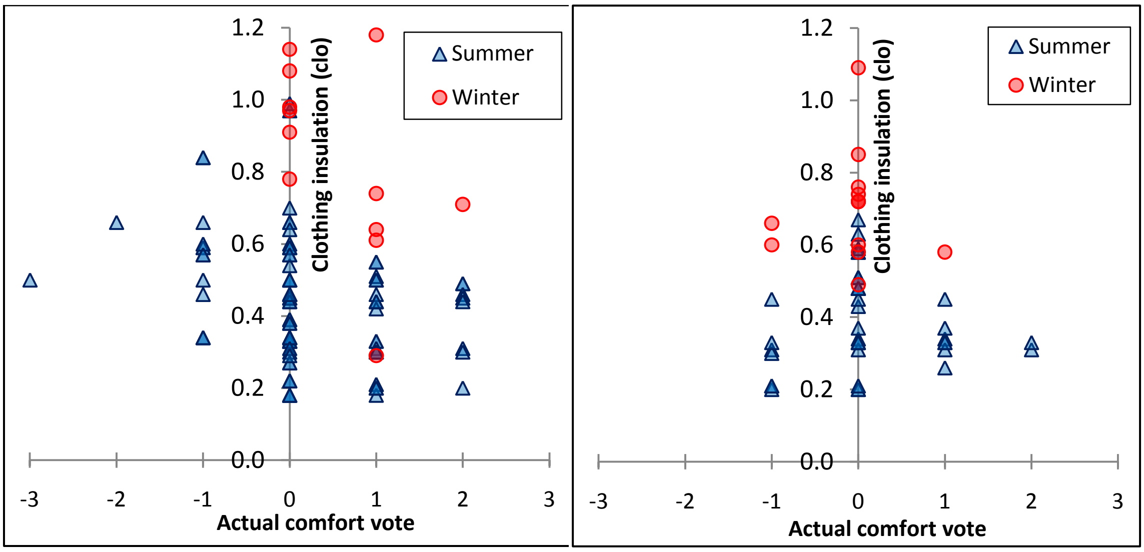


Figure 5.35: Relationship of clothing insulation with the indoor air temperatures for the heavyweight multi-occupancy offices over different seasons.

Some occupants are dressed differently in winter than in the summer despite the indoor air temperatures being the same. This is supportive of the findings of the SCAT project that occupants perceive the same temperatures differently depending on the external conditions, and hence the clothing and expectations will be different for the occupants (Nicol and Humphreys, 2007).

CIBSE (2006) suggests that typical clo values for commercial premises in winter are between 0.8 and 1.0 clo, and in summer are between 0.35 and 0.6 clo. Therefore, some occupants of the offices in this study are *'overdressed'* over summer (clo value of 1.0, which is equivalent to wearing a suit), or *'under-dressed'* in winter (0.3 clo), when compared with the typical clo values (Figure 5.36).



Office NH6 Office SH2

Figure 5.36: Relationship of clothing insulation and actual comfort vote for the multi-occupancy heavyweight offices.

Some of the occupants of the offices were overdressed in winter, and scored their comfort as slightly warm, and have a preferred comfort vote of slightly cooler (e.g. a female occupant in SH2, clothing insulation = 1.36 clo, actual CV = 1, preferred CV = -1). The occupants have to learn to adjust to their environment, and be willing, especially in winter, to take a layer off. An occupant in SH2 who was wearing a t-shirt in winter (overall clothing insulation = 0.5 clo) was neutral with his environment. He had a jumper next to him ready to wear if his comfort changed. Consequently, some occupants are willing to take actions in order to be in thermal neutrality. However, some of the occupants working in the labs preferred to be under-dressed in their office, so that when they go to the labs (which are significantly cooler than the offices), they can wear an extra layer of clothing and feel comfortable. The occupants of office SH2 are dressed significantly different between the two seasons (t = -7.80, p < 0.001), likewise to the occupants of office NH6 (t = -5.97, p < 0.001).

Comparison of the comfort vote (actual and preferred) and the clothing insulation for the two genders was performed for the multi-occupancy offices only (Table 5.23), where the indoor environment conditions (air temperature, air humidity etc.) were approximately the same when the occupants were filling in questionnaires. Over winter, female occupants felt slightly colder than male occupants, despite the female sample wearing clothes with a higher clothing insulation than the male sample.

Table 5.23: Effect of gender on comfort vote and clothing insulation for offices of different thermal mass.

Season	Thermal mass	Gender	Actual comfort vote	Preferred comfort vote	Clothing insulation (clo)
Summer	Lightweight	Male	0.90	-0.42	0.36
		Female	0.75	-0.25	0.47
	Heavyweight	Male	0.24	-0.19	0.36
		Female	0.31	-0.05	0.46
Winter	Heavyweight	Male	0.18	-0.12	0.72
		Female	-0.56	0.56	0.90

Over summer, female occupants are dressed with approximately the same clothing insulation (0.47 clo), despite the thermal mass of the building, likewise to the male occupants (0.36 clo). Previous analysis indicated that the clothing insulation was more correlated with the outdoor air temperature than the indoor air temperature (Table 5.22). Consequently, there is no correlation between the thermal mass of the building and the clothing insulation of the occupants. From the results it can be inferred that female subjects are dressed warmer than male subjects for the same indoor air temperatures, despite season.

During winter (Table 5.24), the occupants of the north-facing offices are dressed (male: 0.87 clo, female: 0.92 clo) on average warmer than the occupants of the south-facing office (male: 0.63 clo, female: 0.88 clo). The female sample, regardless of the orientation of their offices are dressed warmer than the male sample. Males, on average, perceive the indoor air temperature as warmer than females, for the same indoor air temperatures.

Table 5.24: Effect of gender on comfort vote and clothing insulation for heavyweight offices of different orientation.

Season	Orientation	Gender	Actual comfort vote	Preferred comfort vote	Clothing insulation (clo)
Winter	South-facing	Male	0.30	-0.20	0.63
		Female	0.25	0.00	0.88
	North-facing	Male	0.00	0.00	0.87
		Female	-1.20	1.00	0.92
Summer	South-facing	Male	0.21	-0.13	0.39
		Female	N/A	N/A	N/A
	North-facing	Male	0.32	-0.32	0.32
		Female	0.31	-0.05	0.46

5.2.4 Section Conclusion

The occupants of 4E building (lightweight, $CV_{average}$ = 0.69) perceive the indoor air temperatures of their spaces over summer as warmer than the occupants of 6E building (heavyweight, $CV_{average}$ = 0.24), as it is expected, due to the lightweight offices having higher indoor air temperatures. However, over winter, despite the indoor air temperatures of the lightweight offices being warmer than the corresponding temperatures in the heavyweight offices, the occupants were overall cooler (heavyweight $CV_{average}$ = -0.09, lightweight $CV_{average}$ = -0.56). Occupants of the lightweight offices expect higher indoor air temperatures due to the high summer indoor temperatures and over winter perhaps they perceive the temperatures colder than the occupants of the heavyweight building. Perhaps this is related to psychological adaptation of the occupants (past experience and adaptation) (Brager and de Dear, 1998).

The actual thermal comfort vote of the single-occupancy offices is on average better correlated to the outdoor air temperature over summer when the buildings are free-run than during other seasons when mechanical heating is switched on. The preferred comfort vote of the occupants does not always reflect the vote that will take the occupants to thermal neutrality (adjusted thermal sensation for heavyweight offices = 0.19, adjusted thermal sensation for lightweight offices = 0.78).

Unexpectedly, for the same indoor air temperatures, the thermal sensation vote of the occupants in the multi-occupancy offices was lower than the vote given by the occupants in the single-occupancy offices. Perhaps the occupants of the multi-occupancy offices perceived the same amount of control over their offices as the occupants of the single-occupancy offices. Another possibility is that occupants of the multi-occupancy offices have different (lower) expectations than the occupants of single-occupancy offices, similarly to the different expectations of the occupants in the AC / NV buildings (Fountain *et al.*, 1996).

Regarding the multi-occupancy offices, the indoor air temperatures of the lightweight offices have a higher correlation with the actual comfort vote of the occupants when compared to the heavyweight offices. The south-facing heavyweight office has a lower correlation between the comfort vote of the occupants and the indoor air temperature of their space than the north-facing office over summer. The lightweight offices, however, have the opposite correlation, i.e. higher correlation for the south-facing and less for the north-facing. The difference in the relationship between the indoor air temperature and the actual comfort vote over winter and summer is more noticeable for the the north-facing heavyweight office than for the south-facing offices. The correlation between the comfort vote and the outdoor air temperature is stronger for the lightweight offices than for the heavyweight offices. Looking at this correlation for the heavyweight offices over different seasons, it is observed that there is no correlation over winter as the building is not free-run.

Clothing insulation was another area of interest in the subjective data collection. Data suggests that the clothing insulation of the occupants is more influenced by the outdoor air temperatures than the indoor air temperatures. It was further observed that occupants do not like to change their clothing throughout the day despite being in discomfort, and hence in some cases there were occupants that were either over- or under-dressed. For indoor air temperatures below 21°C, the occupants of the single-occupancy lightweight offices were on average more heavily dressed than the occupants of the heavyweight offices. The occupants of the lightweight building were more lightly dressed than the occupants of the heavyweight building for temperatures over 21°C.

The lower thermal mass multi-occupancy offices yield a higher correlation between the clothing insulation of the occupants and the indoor air temperature than when compared to the heavyweight offices over summer. Orientation does not have a significant effect on the correlation between clothing insulation and indoor air temperature for the lightweight offices. This is not the case, however, for the heavyweight offices where the north-facing office exhibits minimal to almost zero correlation. Referring to the seasonal effect of the clothing insulation, for the same indoor air temperatures over winter and summer the occupants of the south-facing office are more heavily dressed.

SUMMARY

Data collected regarding the indoor air temperatures and the thermal sensation of occupants located in two buildings of different thermal mass were analyzed in this chapter. The results suggest that lightweight offices are warmer than the offices located in the building of higher thermal mass. As expected, the occupants in the lightweight offices are feeling warmer in their offices than the occupants located in the heavyweight offices. More detailed analysis was performed where the effect of occupancy levels and orientation of the offices on the indoor temperatures of the offices and the thermal comfort of the occupants was investigated. The following chapter discusses the main findings of this chapter.

Chapter 6

DISCUSSION

The extent of influence of the outdoor air temperature on the indoor air temperature in the buildings studied depends on the operational habits (such as window and door operation) of the occupants and whether the building is free-run or mechanically heated. It also depends on the construction of the building, such as its heat capacity, the orientation of the offices with respect to the north and the sizes of the offices. The ways in which occupants adapt to the indoor air temperature of their offices vary, ranging from using available controls, changing their dressing habits and using portable heating / cooling devices. This chapter discusses the most important findings from the study.

6.1 Factors Affecting Indoor Air Temperature

This section discusses the most important factors that influence the indoor air temperatures in the two buildings studied and the impact of each factor on the thermal sensation of the occupants.

6.1.1 Building's Thermal Mass

As expected over summer, heavyweight offices have a lower correlation with the outdoor air temperature than lightweight offices, with the peak indoor air temperature in the heavyweight offices typically being reached approximately 2 hours later than in the lightweight offices. The lightweight offices over summer had overheating problems (exceeding the suggested temperature of 19 – 24°C by the Carbon Trust), whereas the heavyweight offices were overall cooler and maintained more comfortable indoor air temperatures even during the short mini heat-wave period (22/06/09 – 03/07/09). This supports the findings of Raja *et al*. (2001) and Tuohy *et al*. (2007). Unsurprisingly, the occupants of the lightweight building are slightly warmer than the occupants of the heavyweight building (difference in actual thermal comfort vote of 0.45). None of the occupants in the heavyweight building perceived their indoor environment as hot (unlike the occupants of the lightweight building).

The comparison of offices of the same orientation but different thermal mass suggests that over summer the lightweight offices yield higher indoor air temperatures (up to 10°C higher for east-facing offices, and up to 6°C higher for south-facing offices). The south-facing lightweight multi-occupancy office is warmer than the corresponding heavyweight one (up to 5°C). The differences in maximum indoor air temperatures are greater for the north-facing multi-occupancy offices of different thermal mass (up to 6°C). It can thus be concluded that heavyweight offices are cooler than the lightweight offices over summer. The difference in the indoor air temperature varies depending on the operation of the spaces (Section 6.1.4) and its surrounding environment.

The diurnal temperature fluctuations are in general greater for the lightweight offices than for corresponding heavyweight offices. As concluded by Ward (2004), the heavyweight offices maintain more constant indoor air temperatures than the lightweight ones regardless of the activities taking place in the building, which in this case were the same (sedentary occupants performing desk work).

Likewise to the summer findings, the lightweight single-occupancy offices exhibited a larger variation in their indoor air temperatures (on average 7°C) during late autumn / early winter than the heavyweight ones (on average 3°C). The transition from minimum to maximum indoor air temperature in the lightweight offices usually occurred during the working hours. Humphreys (1992) suggested that diurnal indoor air temperatures with a variation up to ±2°C might still be satisfactory although it is likely to cause discomfort.

During mid-winter the variation during working hours was on average 5°C for the lightweight offices with the average maximum temperature being 21°C and the offices having indoor air temperatures as low as 16°C at 10.00am. On average, the occupants perceived their indoor air temperatures as slightly cool (CV = -1). For the heavyweight offices the average variation was still 3°C during the working day, but the air temperature in the offices was on average 16°C at around 9.00am. Unsurprisingly, the occupants felt slightly cool in their offices (CV = -1), however as the temperature reached 20°C over lunchtime, the occupants were neutral with the environment (CV = 0).

Comparing the adjusted thermal comfort vote of the occupants, the heavyweight building (6E) is more comfortable than the lightweight building (4E) ($M_{heavyweight}$ = 0.19, $M_{lightweight}$ = 0.76).

6.1.2 Office Orientation

Looking at the data collected during summer (over both monitoring periods) it appears that the east-facing offices are warmer than the offices facing north, south or west (Figure 6.1). This supports the findings of Karyono (2000) and Moujalled *et al*. (2008) that east orientated offices are generally warmer. However, the findings suggest that the north-facing offices are the next most vulnerable to high temperatures, followed by the south-facing (and west-facing for lightweight building) offices, contradicting Karyono (2000) and Moujalled *et al*. (2008). The findings are not supporting previous research, due to other factors that influenced the indoor air temperatures of the offices. For example, the west-facing offices are cooler over summer than expected, due to the shading provided by the tree in the courtyard.

Table 6.1: The influence of the office orientation on the indoor air temperature reached in offices over summer.

Thermal mass	Orientation	Indoor air temperature (°C)	Actual comfort vote	Adjusted comfort vote
Lightweight	East	26.6 (4)	0.33	0.09 (1)
	West	23.8 (2)	0.90	1.52 (4)
	South	23.3 (1)	0.73	0.98 (2)
	North	24.8 (3)	0.76	1.02 (3)
Heavyweight	East	23.7 (3)	0.39	0.78 (3)
	South	22.0 (1)	0.10	0.14 (1)
	North	22.7 (2)	0.26	0.34 (2)

Note: the number in the brackets represents the most favorable conditions, with (1) being the highest.

The orientation of the multi-occupancy offices did not have a significant impact on the average indoor air temperatures over summer. For both the lightweight and heavyweight buildings the difference in the average indoor air temperatures between the south- and north-facing offices is 0.3°C (Figure 6.1). However, in both cases, the north-facing offices reached a lower indoor air temperature at night-time than the south-facing offices (3°C for the lightweight and 1°C for the heavyweight).

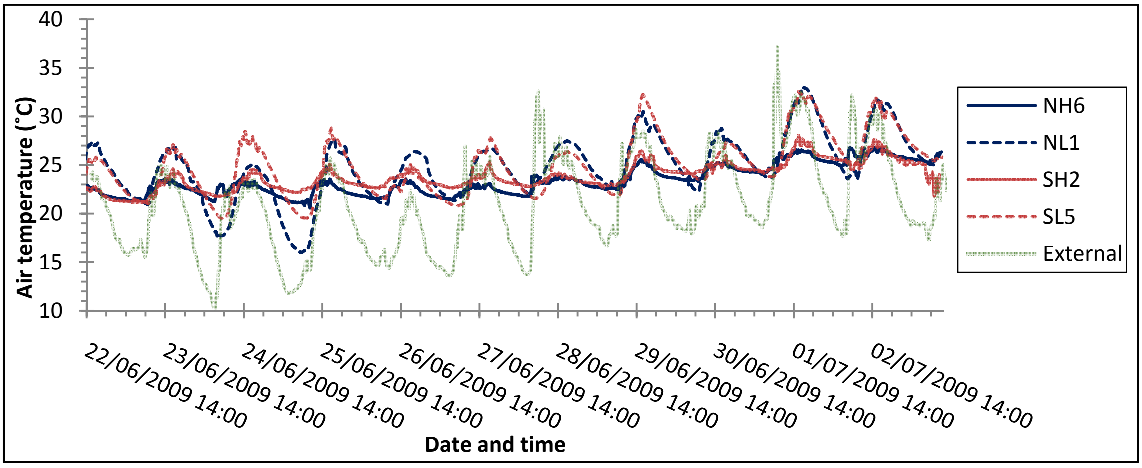


Figure 6.1: Summer indoor air temperature in multi-occupancy offices.

The thermal comfort vote of the occupants of the multi-occupancy offices of opposite orientations was very similar in both cases (Heavyweight CV difference: M = 0.5; Lightweight CV difference: M = 0.4). The occupants of the north-facing heavyweight multi-occupancy offices were warmer than the occupants of the south-facing offices, despite the lower temperature of their office (Figure 6.1). Perhaps the lower indoor temperatures of the north-facing office over winter (on average 4°C) caused the occupants to expect lower indoor air temperatures.

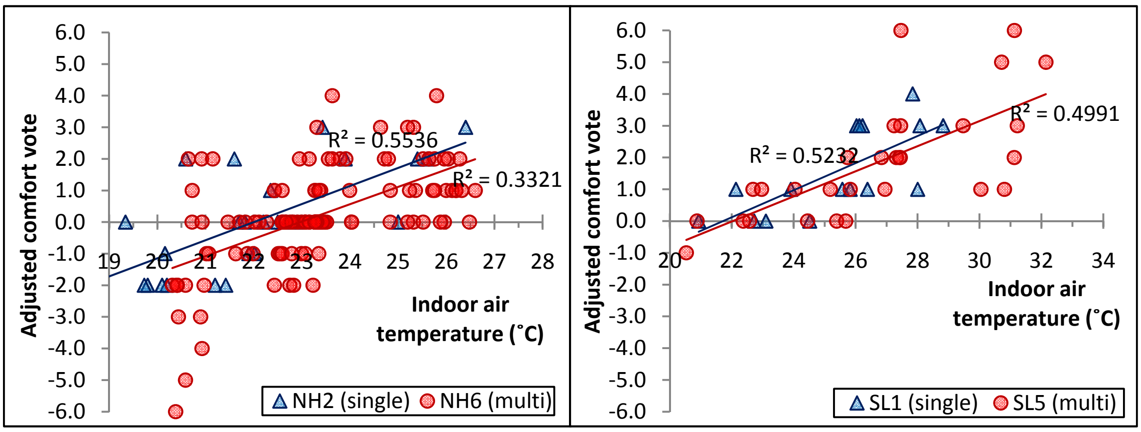
During autumn and winter, where the building has mechanical heating and is not free-run like in the summer, the heavyweight multi-occupancy south-facing offices were constantly warmer than the north-facing office and that was reflected in the thermal sensation votes of the occupants ($ATS_{south\text{-}facing}$ = 0.31 i.e. were slightly warm, $ATS_{north\text{-}facing}$ = -1.29 were uncomfortably cool with the indoor air temperature).

It can therefore be concluded that the orientation of the offices influences the air temperatures reached indoors and hence the expectation and thermal comfort of the occupants. The data suggests that there is no significant difference in the overall (over winter and summer) adjusted thermal sensation votes of the occupants in the north- and south-facing offices. The north-facing offices are just a little more comfortable than the south-facing offices (Multi-occupancy: (i) heavyweight $ATS_{south\text{-}facing}$ = 0.35, $ATS_{north\text{-}facing}$ = 0.17; (ii) lightweight: $ATS_{south\text{-}facing}$ = 1.83, $ATS_{north\text{-}facing}$ = 1.02).

6.1.3 Occupancy Levels

On average, multi-occupancy offices reach higher indoor air temperatures in winter and summer than the single-occupancy offices, and unexpectedly the average adjusted thermal sensation vote of the occupants suggests that the multi-occupancy office occupants are warmer than the occupants of the single-occupancy offices (ATS difference = 0.3). Most of the occupants of the multi-occupancy offices perceived their indoor environment as uncomfortably warmer than the occupants of the single-occupancy offices. The difference between the perceived comfort of the two sets of occupants located in the lightweight offices is more significant than in the heavyweight offices. Consequently, it appears that the size of the offices is more important for lightweight offices. The availability of controls in the offices is more important for the multi-occupancy offices.

Over the heat-wave week the single-occupancy north-facing heavyweight office was cooler by approximately 1°C than the multi-occupancy north-facing heavyweight office. The single-occupancy south-facing lightweight office was cooler than the multi-occupancy south-facing lightweight office by 2.5°C. However, when comparing the adjusted thermal comfort vote for the different occupancy levels, it appears that for the same indoor air temperatures the occupants of the multi-occupancy office are slightly more comfortable than the occupants of the single-occupancy offices. Perhaps the occupants of the multi-occupancy office had lower thermal expectations.



Heavyweight offices

Lightweight offices

Figure 6.2: The relationship between adjusted comfort vote and the indoor air temperature for offices of different occupancy levels.

6.1.4 SPACE OPERATION

The correlations of the indoor and outdoor air temperatures for the offices located in the heavyweight and the lightweight buildings vary depending on the season. Over summer the indoor air temperatures are more dependent on the outdoor air temperatures as the buildings are free-run, than over winter where they are mechanically heated, supporting the conclusions of Humphreys (1981). The correlation between the indoor and outdoor air temperatures varies even between offices of the same orientation and thermal mass, suggesting that the occupants' operation of the spaces has an impact on the indoor air temperature, as was observed by Yun *et al*. (2008) in his study of offices in Cambridge. Although offices of the same occupancy levels, thermal mass and orientation follow the same diurnal indoor air temperature patterns, they have significantly different temperatures throughout the day and this can be attributed to the different operations of the spaces by the occupants.

For example, the maximum indoor air temperature of the south-facing multi-occupancy lightweight office over summer is lower than the temperature reached in the north-facing one. However, the south-facing office had less occupants present on those days (up to four people less), and the office is smaller, all contributing to extra heat gains. Further, the occupants of the south-facing office had all their windows (four) and the door open, enabling cross ventilation whereas the north-facing office had two windows open (all available) and the door closed most of the time. Therefore it can be concluded that the difference in the indoor air temperatures is largely affected by the operation of the spaces and the number of occupants present. The operation of the windows suggests that occupants open them in an attempt to reduce their discomfort. As suggested by Yun *et al.* (2008), in temperate climates such as in the UK, opening windows on a hot day in order to achieve thermal comfort (through ventilation) is possible. If the windows are kept closed, the indoor air temperatures will increase due to the solar gains from the windows, and the heat can only escape from the room by conduction, which is much slower than through an open window.

Another example of the extent of influence on the operation of the spaces is the constant 3°C warmer difference in two adjacent west-facing lightweight single-occupancy offices during the spring period. The male occupant (WL1) had turned the thermostat on the lowest possible setting in his office, and almost always had both his window and door open throughout the working day. On the other hand, the female occupant (WL5) had her windows and door almost always closed and was using a personal portable heater, in addition to the radiator in her office when present in her office.

During the same spring period the data suggests that for the heavyweight offices female occupants maintain higher indoor air temperatures than male occupants during the day-time (up to 6°C), but at night-time they reach the same indoor air temperature (within 0.5°C). Both occupants had their windows and doors open when present in their respective offices and had their office radiator on. However, the female occupant had her personal heater on for the majority of the time. Instead of operating the windows as a control of the indoor air temperatures, she was mostly using her own personal heater located directly next to her. The difference between the indoor and outdoor temperature at night-time is lower for the low thermal mass building (11°C) than for the heavyweight one (15°C).

None of the occupants located in the heavyweight building (multi- or single-occupancy offices) used assisted ventilation in the offices, unlike in the lightweight offices. Both lightweight multi-occupancy offices used fans over the summer monitoring, and 50% of the single-occupancy monitored that week. In one extreme case, one of the occupants (single-occupancy south-facing office) had installed an air conditioning unit over that summer period, as he could not stand the indoor air temperatures in his office. Regarding the lightweight multi-occupancy offices, there were occupants who did not come in, as they were influenced by the weather forecast and their thermal experience of the previous day.

6.2 Indoor Air Temperature and Occupants' Adaptation

Correlating the indoor and outdoor air temperatures with the actual thermal comfort vote of the occupants indicated that the relationship varies depending on the season. The comfort vote in the majority of the single-occupancy offices (despite thermal mass) was influenced more by the indoor air temperature than the outdoor air temperature. The relationship with the outdoor air temperature was stronger over summer when the building is free-run.

Over winter, the comfort vote of the occupants of the multi-occupancy office is influenced by the indoor air temperatures and not by the outdoor air temperatures. The female subjects felt slightly colder than the male subjects, despite the female subjects wearing clothes with a higher clothing insulation than the male subjects. Occupants of the heavyweight multi-occupancy offices were dressed differently in winter than in summer despite the indoor air temperatures being the same at times. Like in the SCAT project, it appears that the occupants perceive the same temperatures differently depending on the external conditions, and hence the clothing and expectations of the occupants is different (Nicol and Humphreys, 2007).

Over summer there is a higher correlation between the actual comfort vote of the occupants and the indoor air temperature for the lightweight offices than the heavyweight offices. Nevertheless, the outdoor air temperature influences the comfort vote of the occupants as much as the indoor air temperature. This is due to the building being free-run over summer and hence the indoor air temperatures are strongly correlated to the outdoor air temperature. Although the thermal comfort vote of the occupants over summer was different between the occupants of the two buildings (average $CV_{lightweight}$ = 1.00, average $CV_{heavyweight}$ = 0.20) the occupants were dressed similarly. The female occupants were dressed with approximately the same clothing insulation (0.47 clo), despite the thermal mass of the building, likewise to the male occupants (0.36 clo). This could perhaps be explained by the findings of Baker and Standeven (1996) and de Carli *et al.* (2007) that morning outdoor temperatures highly influence the clothing occupants chose to wear for NV buildings. From the results it can be inferred that female subjects are dressed warmer than male subjects for the same indoor air temperatures, despite the season.

If more sensors were available the study could be extended to investigate the environment the occupants were exposed to an hour and a half before filling in the questionnaires as suggested by Chun *et al*. (2008). This would be more appropriate for the multi-occupancy offices when investigating what influenced the discrepancies in the comfort votes of the occupants for the same indoor air temperatures (Nicol and Humphreys, 2007).

It was also observed that women do not like to make alterations to their clothing throughout the day despite being in discomfort, and hence, in some cases there were occupants that were either over- or under-dressed. For indoor air temperatures below 21°C, the occupants of the single-occupancy lightweight offices were on average more heavily dressed than the occupants of the heavyweight offices. The occupants of the lightweight building were more lightly dressed than the occupants of the heavyweight building for temperatures over 21°C.

Over the summer monitoring period, some of the male subjects had to attend formal meetings, where they had to wear formal clothing (long trousers and shirt). Some of them were coming in with shorts and t-shirt and changing into formal clothing for the meetings. These findings coincide with the suggestion of Morgan *et al*. (2003) that dress codes do not represent what the occupants would like to wear.

Further, the occupants in both the multi- and single-occupancy offices were complaining about the radiators not being in an easily accessible location, supporting the findings of Karjalainen *et. al* (2009). However, regarding the operation of windows, occupants in the single-occupancy offices were complaining that they are the only form of ventilation, whereas in the multi-occupancy offices people sitting away from the windows are not aware of the number of windows that are open in the office.

6.3 Implications of the Findings on the Energy Use

Although the exact energy wastage has not been calculated, the information suggests that there is unnecessary energy usage in the buildings monitored. The lightweight offices has the highest usage of personal heaters and fans compared to the heavyweight offices. Over winter 40% of the occupants of the offices had an extra personal heater in their office. It might be better to increase the temperature in offices by 1°C over winter to avoid the use of personal heaters. Energy consumption analysis should be performed in order to find the most energy efficient way to achieve thermal comfort.

Further, many occupants have mentioned during the study that they do not actively use their TRVs during the heating period, as they are not easily reachable (usually located behind desks). This leads the occupants to have windows open when the heating is on leading to more energy wastage. For example, in one case, the occupant had the window open when the outdoor air temperature was quite low (7°C) resulting in indoor air temperatures of 14°C, and consequently unnecessary energy wastage as the radiator was on. Another occupant always had the window open as it was obstructed by equipment and hence was not easily reachable. This same occupant was using a personal heater to adjust the indoor air temperature of the office.

A significant number of the occupants of the offices (56%) have a fan operating in their office over summer and in one case installed an AC system. This finding supports the findings of Raja *et. al* (2001) that as temperatures rise above the mid 20°C the usage of the fans in offices reaches 50%. The installation of a personal AC unit in the office of one of the occupants perhaps suggests that it is a matter of time until more occupants will demand mechanical cooling in their offices over summer, especially since the high temperatures start to interfere with their working conditions. With the occupants having their own cooling devices in their office no-one can control the temperature they set, and could result in unnecessary energy wastage, and needless to say this is not ideal in terms of the CO_2 emissions.

Before installing ACs, other possible ideas should be investigated such as external solar shading to block the direct sunlight from coming in. Lightweight offices have a high percentage of glazing on their external wall, and it was shown that west-facing offices that had the shade of the tree had lower indoor air temperatures than the east-facing ones.

SUMMARY

It was concluded that the higher the thermal capacity of the building the more comfortable it is for the occupants. The air temperature reached in offices depends on the operation of the spaces, any external shading and the orientation of the offices (with east-facing being the worst orientation).

Further, it was discovered that there is a lack of active operation of thermostats in the offices over winter in both buildings. There is a high usage of fans and personal portable heaters, especially in the lightweight building. It can thus be inferred that there is significant unnecessary energy consumption. Further, females usually maintain higher indoor air temperatures in their offices than male occupants. The following chapter concludes the findings of the study.

Chapter 7

CONCLUSION

Two buildings of different thermal properties (heavyweight and lightweight) were studied in the University of Bath. In total, 22 offices were monitored (18 single-occupancy and 4 multi-occupancy), collecting over 100[i] different data files and a total of 520 questionnaires. It is acknowledged that the scale of the project was small, and hence many of the findings that will be outlined in this chapter are applicable to the two buildings studied and cannot necessarily be generalized.

7.1 Summary of Main Findings

Over summer, when the buildings are free-run, there is a higher correlation between the outdoor air temperature and the indoor air temperature of the lightweight offices than for the heavyweight offices. The heavyweight offices have diurnal indoor air temperatures with low amplitude (~3°C) whereas the lightweight offices have a high variation in the indoor air temperatures (~7°C), causing more discomfort to the occupants. Occupants choose adaptive opportunities such as operating their windows and opening doors in attempts to reduce thermal discomfort.

The data suggests that overall the lightweight offices are warmer than the heavyweight offices for all the seasons. Over summer, the lightweight offices reach high temperatures (up to 38°C) that disrupt the occupants; some do not come into the office after looking at the weather forecast, whereas others use fans or in one case the occupant installed an AC unit in an

[i] Data files include indoor and outdoor air temperatures, window and door operation, and carbon dioxide levels.

attempt to reduce discomfort. At the same time, the heavyweight offices reach indoor air temperatures of 28°C, which lie within the acceptable indoor temperatures of 19°C and 29°C.

During the winter period the heavyweight offices are cooler during the day-time (maximum difference ~2°C), but at night-time are warmer (by ~3°). The occupants however, perceive the indoor air temperature as slightly cool in both buildings as the average indoor air temperature is 18°C. Over spring and autumn some of the occupants perceive the indoor air temperature of their office as too warm, and are opening their windows without altering the state of their thermostat. The occupants often reported that they could not reach their thermostat, and they assumed that it was always on at the maximum level.

The orientation of the offices affects the indoor air temperatures for the single-occupancy offices, with the east-facing reaching the highest indoor air temperatures. For the multi-occupancy offices, orientation of the offices does not have a significant effect on the indoor air temperatures reached by the offices. The extent of influence of the outdoor air temperatures on the indoor air temperatures of the offices coincides with the findings of Raja *et al*. (2001); namely that it depends on the building characteristics but also on the available controls and their appropriate usage by the occupants of the offices.

Further, the clothing of the occupants is not altered in an attempt to reduce discomfort. Female occupants are reluctant to change their clothing throughout the day despite being in discomfort, as they see their clothing as what they should wear for the day. The clothing the occupants wear is highly dependent on the outdoor air temperatures. Consequently, it can be concluded that the morning temperatures influence what the occupants wear for the day.

To conclude, the findings suggest that thermal mass affects the indoor air temperatures reached in the educational offices mostly over summer, and hence the comfort of the occupants. There is more unnecessary energy usage in the lightweight offices, caused by the occupants trying to eliminate discomfort by using assisted ventilation or air-conditioning systems. Most educational offices however, have already been constructed, and hence it is important to look into the most effective way of increasing their thermal mass in order to eliminate the need for mechanical cooling.

7.2 Effective Refurbishments

Multivariate Analysis of Variance (MANOVA) was performed on the data collected to rank some of the building properties (thermal mass, office orientation and occupancy levels) in order of impact on the indoor air temperatures of the offices and the thermal sensation (actual and adjusted) of the occupants. As expected, the thermal capacity of the building is one of the most significant factors affecting all the variables tested (actual and adjusted thermal sensation and indoor air temperature). Unexpectedly, the most significant variable is the occupancy levels of the offices (for all variables) and is followed by the orientation of the offices.

Consequently, if new educational office buildings are constructed, they should be made with a high thermal capacity (i.e. has to be a heavyweight building), and the spaces should be designed so that there are more single-occupancy offices rather than multi-occupancy offices. East-facing offices should be avoided, as they tend to have overheating problems.

Most of the current building stock in the UK will not be replaced in the next 70 years (CIBSE, 2005a) and hence increasing the thermal mass of the buildings may not be an effective solution, therefore other adaptation strategies must be considered. In the UK, where most educational buildings have already been constructed, it may be more cost-effective to refurbish than rebuild them. Further, new buildings are often wrongly regarded as more efficient and *'prestigious'* than the older office buildings (Burton, 2001). Burton (2001) mentions that refurbished buildings could perform better than new buildings as it is not just the design of the building that contributes to the overall quality of the building and its energy efficiency, but the knowledge of how to operate the spaces.

Adding thermal mass to existing buildings however, will not only decrease the usable area but is also a costly solution. However, suspended ceilings could be removed to expose the concrete and hence increase the thermal mass of the offices, which is an option for building 4E. However, as suggested by the Concrete Centre, it might not be a feasible option for many of the buildings constructed in the 1960s and 1970s due to the surface underneath the suspended ceiling being either in poor condition or impractical to relocate all the services located in that space (de Saulles, 2005). Consequently, emphasis should be placed on re-arranging the offices, such that there are more single-occupancy offices, and if possible located in areas where there is shading. Although the temperatures reached in the offices regardless of occupancy levels is almost identical, occupants in single-occupancy offices appear to be more forgiving of the high (summer) / low (winter) indoor temperatures than the occupants of the multi-occupancy offices.

Indoor air temperatures reached in the offices suggest that the orientation of educational buildings will impact the temperature they reach, with east-facing offices always being warmer than offices facing in other orientations. Overall there was no correlation between the thermal sensation of the occupants and the office orientation, and hence based on the average indoor air temperatures, the preference for the orientation of offices should be (1) north, (2) south / west and (3) east (assuming the same amount of glazing and office dimensions). Regarding the multi-occupancy offices, it appears that the north-facing offices are slightly more comfortable than the south-facing offices, and hence they should be preferred. However, as observed by Mallick (1996), north-facing rooms are the least-preferred option due to the lack of direct sunlight, and so perhaps north-facing offices might not be an ideal solution.

The findings of the study suggest that NV educational buildings could be comfortable, and hence the installation of AC systems can be avoided through careful design / refurbishment, and by understanding the occupants needs.

7.3 Further Work

In order for the findings to be applicable on a larger scale, such as providing general information on refurbishment of educational office buildings, a more extensive study would be required. More than two buildings of different thermal capacities would be required for the study. The buildings should ideally all be located in the same part of England (to avoid the effect of local climates / urban heat island effect etc.).

The number of occupants per building would need to be over 141 in order to be confident that any insignificant relationships between the thermal capacities of the building and the thermal comfort of the occupants is not due to small sample size. The sample size was calculated using the program G*Power 3.1.2 (Faul, *et al*., 2009), where the mean and standard deviation for the adjusted thermal sensation of the occupants in the buildings of different thermal mass (4E and 6E) monitored for this thesis were used (the values used are those in Chapter 5, Figure 5.23). Once the effective size was calculated, the sample size per group required for significant differences in mean values for independent samples to be detected was calculated. This was 141 people per group. If the sample size calculation was based on actual thermal sensation (input data from Chapter 5, Figure 5.22), 94 people per group would be required. Consequently, it is important to take the largest of the two to be sure that any insignificant differences cannot be attributed to small sample size. In total, a minimum of 1294 people have to be used in the survey (647 based in single-occupancy offices and 647 located in multi-occupancy offices) (this is based on statistical sampling and the data used for this calculation are those in Chapter 5, Figure 5.29).

The findings could then be inputted to calibrate a model which can be used to predict effective refurbishments of educational buildings in England. Through the modeling phase the building parameters such as construction date, size of offices, thermal capacity, external shading caused by the trees, operation of windows etc. can be taken into account and suggestions can be made regarding the most applicable refurbishment measures for educational office buildings.

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Appendix 1

LONGITUDINAL QUESTIONNAIRE

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UNIVERSITY OF BATH

Questionnaire to assess environmental
aspects of your spaces

Before replying to the questionnaire, please ensure that you have been in your office for at least 15 minutes.

1. How warm do YOU feel in your office now?

Very hot 1 2 3 4 5 6 7 Very cold

Comments:________________________

2. How warm do YOU wish you could feel now?

Much warmer 1 2 3 4 5 6 7 Much cooler

Comments: ________________________

3. Do you have any cooling or heating device e.g. a fan, working in your office now?

Yes / No

If YES please specify: ____________

Comments: ________________________

4. How noisy is it in your office now?

Noisy 1 2 3 4 5 6 7 Quiet

If it is noisy, please circle the type of noise:

External noise from window Yes / No

Corridor noise from door Yes / No

Other (please specify) ________________________

Please tick the boxes that apply to the clothes you are wearing in your office now. If you are wearing more than one of any item, please specify the number in the brackets.

☐ Short sleeved shirt ( )	☐ Sleeveless vest sweater (thin) ( )	☐ Shorts ( )
☐ Long sleeved shirt ( )	☐ Calf length normal socks ( )	☐ Trousers ( )
☐ T-shirt ( )	☐ Ankle-length athletic socks ( )	☐ Boots ( )
☐ Long sleeved sweater (thin) ( )	☐ ¾ shorts ( )	☐ Shoes ( )

Other (please specify) ________________________

Information about completion of the questionnaire:

Date: ____________ Time: ____________

Thank you very much for your time.
Michelle Lakeridou

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Appendix 2

TRANSVERSE QUESTIONNAIRE

UNIVERSITY OF BATH

Questionnaire to assess environmental aspects of your spaces

The aim of this questionnaire is to enable us to find more information about the internal environment of your spaces, how comfortable you feel inside, and where most energy loss is occurring. The questionnaire is divided into three sections, and we kindly ask that you complete all of them. All data collected from this questionnaire will be kept anonymous, and shall be protected under the Data Protection Act 1998.

Section A:

This section concentrates on your likes and dislikes of certain environmental aspects of your office and how important each factor is to you. For example, you may slightly dislike your office temperature and hence circle -1 on the liking scale. However, the temperature factor could be very important to you and so you circle 3 on the importance scale.

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
1. Electric lighting	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
2. Glare level	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
3. Office temperature	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
4. Humidity	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
5. Ventilation	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

	Liking Scale (Dislike ← → Like)	Importance Scale (Unimportant ← → Important)
6. Draught level	−3 −2 −1 0 1 2 3	−3 −2 −1 0 1 2 3

Comments: ______________________________

7. Odours

Dislike						Like		Unimportant						Important
-3	-2	-1	0	1	2	3		-3	-2	-1	0	1	2	3

Comments: ____

8. Window size

Dislike						Like		Unimportant						Important
-3	-2	-1	0	1	2	3		-3	-2	-1	0	1	2	3

Comments: ____

9. Noise level

Dislike						Like		Unimportant						Important
-3	-2	-1	0	1	2	3		-3	-2	-1	0	1	2	3

Comments: ____

Section B:

Section B rates different environmental aspects of your office. In some cases you are asked to rate your room from a scale of 1 to 7, in which case, please circle the most representative number. In other cases a yes or no answer must be circled, or the most appropriate box ticked. Unless told otherwise assume that the question refers to the general conditions in your office and not at that particular moment in time.

1. How good is the daylight in your office?

Very bad 1 2 3 4 5 6 7 Very good

Comments: ____

2. How good is the electric light in your office?

Very bad 1 2 3 4 5 6 7 Very good

Comments: ____

3. How bright is it in your office due to the daylight?

Very dark 1 2 3 4 5 6 7 Very bright

Comments: ____

4. How bright is it in your office due to the electric light?

Very dark 1 2 3 4 5 6 7 Very bright

Comments: ____

5. Is there glare anywhere in your office due to the daylight?

High glare 1 2 3 4 5 6 7 No glare

Comments: ____

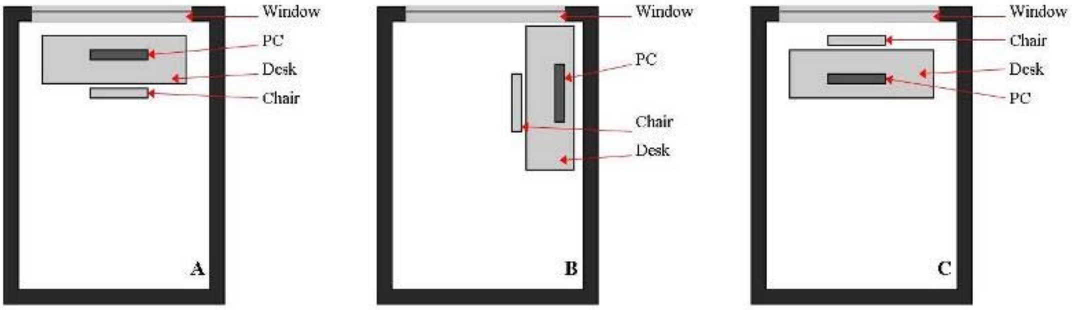
6. Is there glare anywhere in your office due to the electric light?

High glare | 1 | 2 | 3 | 4 | 5 | 6 | 7 | No glare

Comments: ____________________

7. Which of these diagrams best represents your PC's position with respect to the window?

Please tick A ☐ B ☐ C ☐



Comments: ____________________

8. How often do you open the blinds?

Never | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Always

Comments: ____________________

9. How warm is it in your office in general?

Very hot | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Very cold

Comments: ____________________

10. How warm is it in your office now?

Very hot | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Very cold

Comments: ____________________

11. How warm do you wish you could feel now?

Much warmer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Much cooler

Comments: ____________________

12. Is your radiator easily accessible?

Yes / No

Comments: ____________________

13. How often does the temperature vary throughout the day in your office (i.e. how often does the temperature go up and down)?

Very frequently 1 2 3 4 5 6 7 Never

Comments: ____________________

14. How humid is it in your office in general?

Very dry 1 2 3 4 5 6 7 Very humid

Comments: ____________________

15. How humid is it in your office now?

Very dry 1 2 3 4 5 6 7 Very humid

Comments: ____________________

16. Is the ventilation adequate in your office?

Very bad 1 2 3 4 5 6 7 Very good

Comments: ____________________

17. What is the air movement like in your office?

Very draughty 1 2 3 4 5 6 7 Still

Comments: ____________________

18. How much fresh air is entering your office now?

Not enough 1 2 3 4 5 6 7 Too much

Comments:

____

19. If there are any odours in your office now, how strong are they?

Overpowering odour 1 2 3 4 5 6 7 No odour

Comments: ____________________

20. How often do you open your window?

Never 1 2 3 4 5 6 7 Always

Comments: ____________________

21. Is your window open now?

Yes / No

Comments: ____________________

22. When you open your window, how distracting is the noise from the outside?

Very distracting 1 2 3 4 5 6 7 Not distracting

Comments: ____

23. When your door is open, how distracting is the noise from the corridors?

Very distracting 1 2 3 4 5 6 7 Not distracting

Comments: ____

24. What electrical equipment do you have in your office?
Please tick the relevant boxes.

☐ PC ☐ Laptop ☐ Printer ☐ Desk lamp ☐ Mobile charger
☐ Own heater ☐ Plant ☐ Other (please specify)

Other: ____

Section C:

Gender: Male / Female

Age Group: below 20, 21–30, 31-40, 41-50, 51-60, above 61

Office Number: ______________

Information on the timing of completion of the questionnaire:

Date: ______________ Time: ______________

Please feel free to comment on the questionnaire.

Thank you very much for your time.
Michelle Lakeridou, Department of Architecture and Civil Engineering, University of Bath

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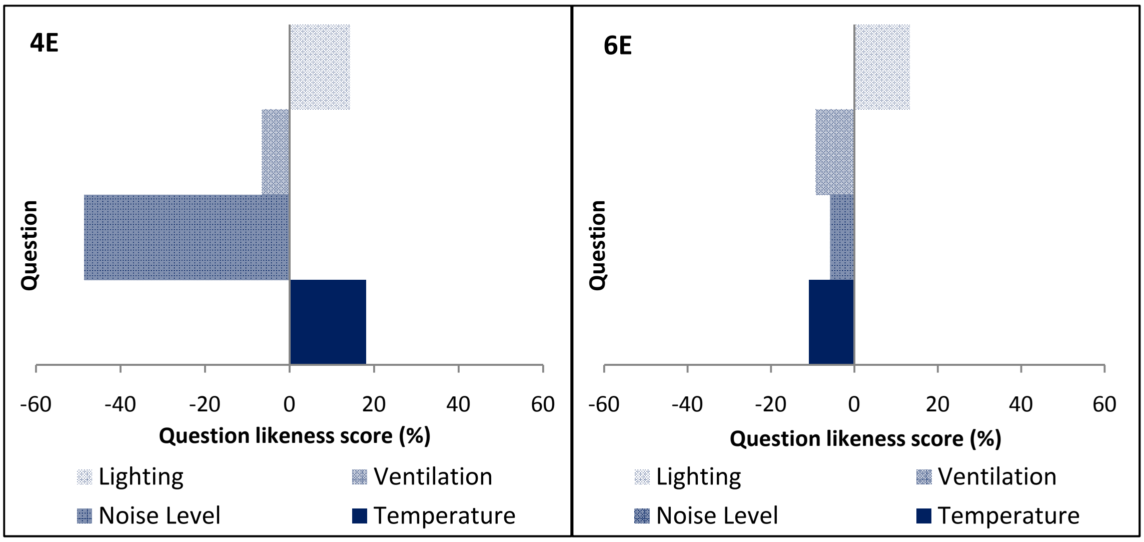
Appendix 3

FINGERPRINTING

Fingerprinting gives an insight in to how various environmental factors could influence the thermal comfort vote of the occupants, whether directly or indirectly. The occupants were asked to rate several factors on a scale of -3 to 3, relating to how much they liked and how important that factor is for them (Levermore and Leventis, 1997)[i]. The likeness score (overall rating of the building /offices) and the likeness fingerprinting (of each individual factor asked in the questionnaire) of the building was calculated. The first step to calculating both is to change the importance vote to a positive value by adding a 4 and then multiplying it by its corresponding liking vote. The higher it is on the positive scale the more the factor is liked and is important to the subject and vice versa (Levermore, 1994).

During the winter phase of the monitoring, the aim of the first section of the questionnaires was to calculate the fingerprinting of various factors that affect the thermal environment such as ventilation, window size, indoor air temperature, etc. The aim of this section of the questionnaire was to get an indication of the occupants' perception on their indoor environmental factors, in terms of likeness and importance to them, and hence assist in understanding the way these factors affect their comfort vote. The various factors from the 4E and 6E buildings are compared directly on top of each other (Figure 1) to enable a comparison between the buildings and amongst the various factors themselves.



Lightweight offices **Heavyweight offices**

Figure 1: Likeness fingerprint for lighting, noise level, ventilation and temperature for winter.

There was a dislike in both buildings with respect to the ventilation of offices. After informal interviews, it was found that the occupants of the single-occupancy offices shared the common dislike of their spaces being ventilated only through windows and doors. At times, opening a window was not a viable option due to draughts or due to noise levels, as the offices are located opposite architectural studios or in busy corridors. This was also indicated by the high percentage of dissatisfied fingerprinting for the noise levels, and it was one of the comments made during the monitoring of the offices. With respect to the multi-occupancy offices, an additional problem was the location of the windows. The occupants had difficulty opening them as they are located behind desks, and the desks are placed along the walls. Furthermore, if a person sitting next to the window was not content with the indoor air temperature, they

[i] References can be found in the Bibliography.

would adjust the window opening accordingly and not necessarily care about others in the office.

The temperature likeness suggests that occupants were content with their indoor air temperature for the lightweight building but not for the heavyweight building. However, when breaking down the temperature likeness score of the 6E offices, it seems that the type of office and orientation influences the score (Figure 2).

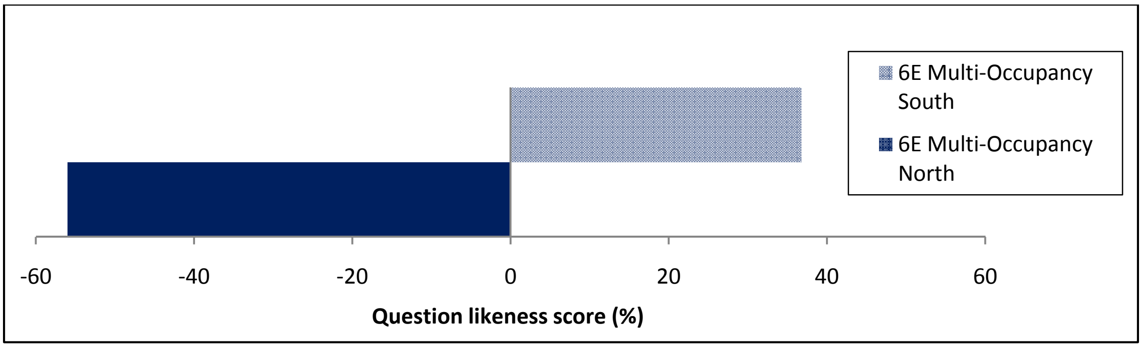


Figure 2: Comparing the temperature likeness fingerprint for different orientations of multi-occupancy heavyweight offices.

The occupants of 4E like the temperature in their office, with a fingerprinting score of approximately (+)20%, but commented that it is different over summer. During the early autumn monitoring there was a sign of overheating periods, but over the winter monitoring, the temperatures were within the suggested ranges (Chapter 5: Figures 5.18 and 5.19).

There is a large discrepancy between the multi-occupancy offices monitored in the 6E building. The occupants of the multi-occupancy north-facing offices were quite dissatisfied, with a fingerprinting score of approximately (-)55%, whereas the occupants of the south-facing office like their office air temperature (approximately (+)40%). The north-facing offices do not get any direct sunlight and hence are significantly cooler than the south-facing ones (t = 110, p = 0.001) (Chapter 5: Figures 5.23 and 5.24). Although the north-facing office air temperature lies within the suggested range by BS EN 13779 (2007) over winter, it is towards the lower end (suggested minimum 19°C, but reaches 18°C at times during working hours), whereas the south-facing offices sometime exceed the suggested air temperatures for winter (suggested maximum of 24°C, but reaches 26°C). The average air temperature of the north-facing office is 18°C (<19°C) whereas the south-facing often has an average of 22°C over the December monitoring period (Chapter 5: Table 5.9).

Over October and November, the single-occupancy office indoor air temperatures were within the suggested range by BS EN 13779 (2007) (Chapter 5: Figures 5.18 and 5.20). However, over January, the indoor temperatures were below the suggested minimum at points throughout the working day (Chapter 5: Figures 5.21). At some points, occupants had turned off their radiators (through the thermostats' valve) in their room as they were feeling hot, yet the un-insulated pipes running along the walls next to the occupants and their desks caused the indoor air temperature to remain high.